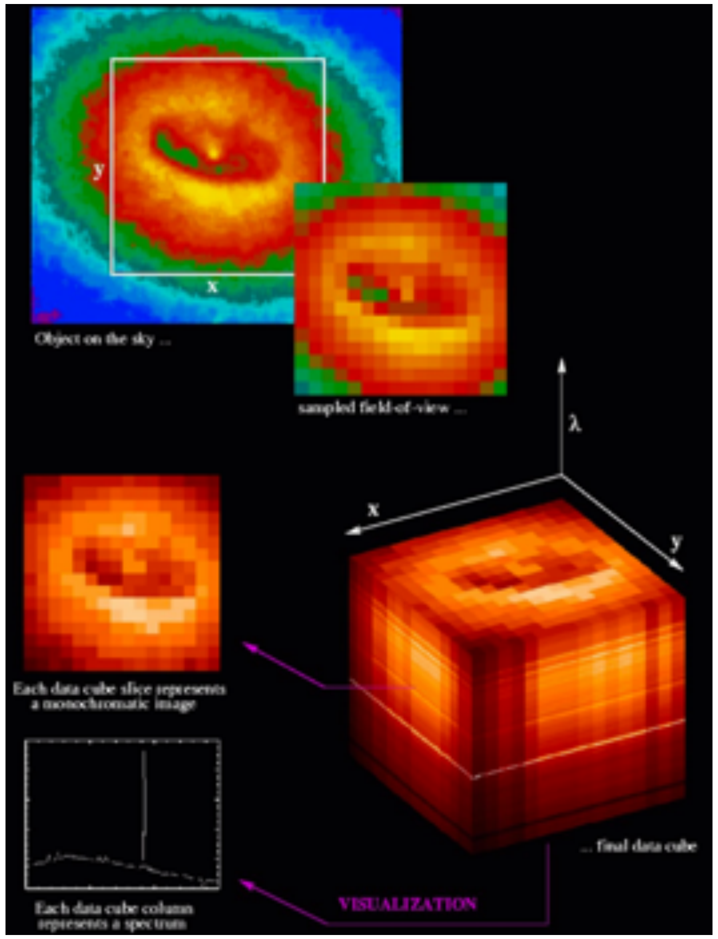
On the Integral Field Spectroscopy as a promissory technique in Remote Sensing

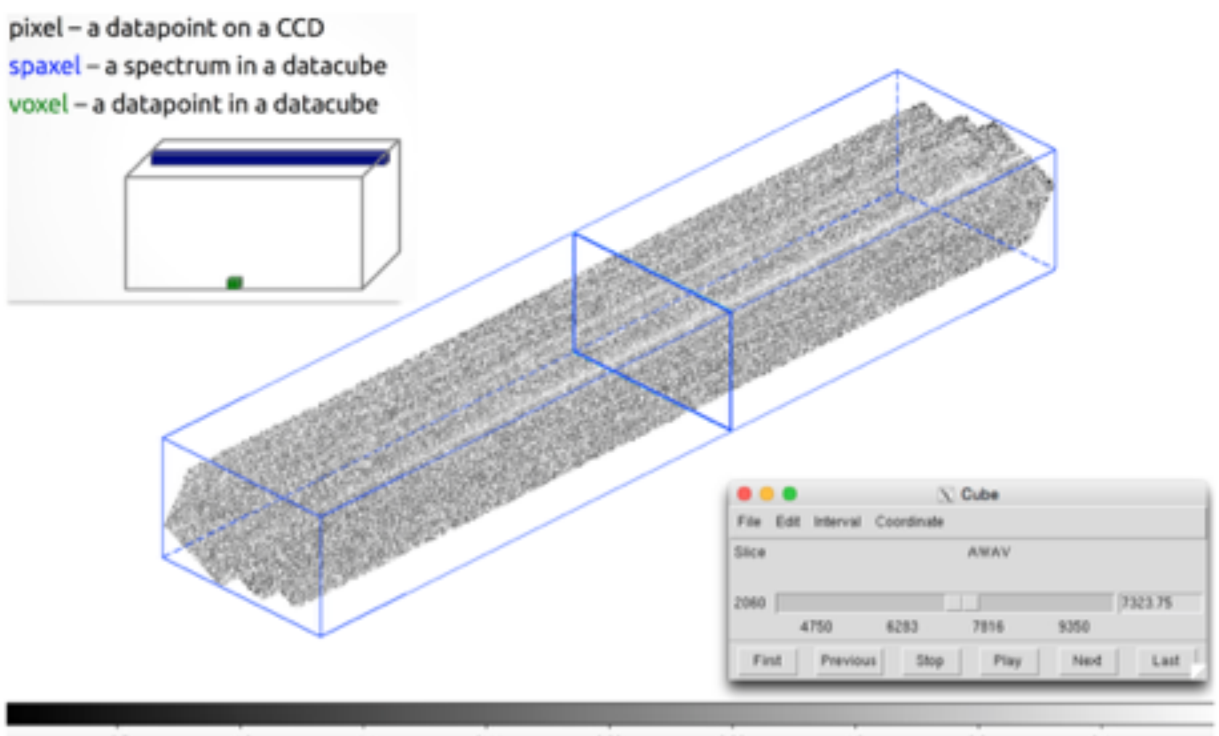
Camilo Delgado, María Moreno, Alexander Páez

Universidad Distrital FJC, Instituto Geográfico Agustín Codazzi - IGAC

The Integral Field Spectroscopy - IFS has emerged as a powerful technique in modern astronomy, offering simultaneous spatial and spectral information of celestial objects, showing remarkable potential as a technique for remote sensing applications. In this document, We will give a comprehensive review of the state-of-the-art advancements in IFS instrumentation, data processing, and scientific applications, discussing its fundamental principles, highlighting key instruments and their capabilities, exploring cutting-edge data analysis techniques, and showcase the scientific breakthroughs enabled by IFS across various fields of astrophysics and observational cosmology. Therefore, We will examine how IFS could be used in remote sensing, showing the advantages of this technology over traditional remote sensing techniques, exploring recent advancements in this field, and showing the advantages to incorporate Integral Field spectrographs to the optical systems that are part of the Earth, Moon and Planets observation Satellites.

Integral Field Spectroscopy-IFS





Schematic definition of the Integral Field Spectroscopy-IFS jargon shown on the MUSE-VLT MACS 1206 datacube. The data slice has taken at $\lambda_{observed} = 7323.75$Å.

MUSE-VLT Datacubes

The Multi Unit Spectroscopic Explorer - MUSE is an Integral-Field Spectrograph as a part of the second generation instruments at VLT [235, 236, 237, 228] with a estimated cost of 21M€[238]. It was developed to have 24 Image slicers [239], 24 Spectrographs [5] and, 24 red sensitives CCDs ($(4k)^2$)[6] as a detectors, being part of an optical design that define each one of the 24 identical Integral Field Units (IFUs) of this instrument. (see Fig. 2.8).

The MUSE data product is a data cube with spectral resolving power R ($\frac{\lambda}{\Delta\lambda}$) of 1770 at 4800Å and 3590 at 9300Å giving a $\sim$ 2.3Å of spectral resolution in all spectral range (4750Å - 9350Å) [242, 243], spectral sampling of 1.25Å/pixel & spatial pixel scale of 0.2″/pixel [244], and Field of View (WFM)[7] of 1′x 1′.

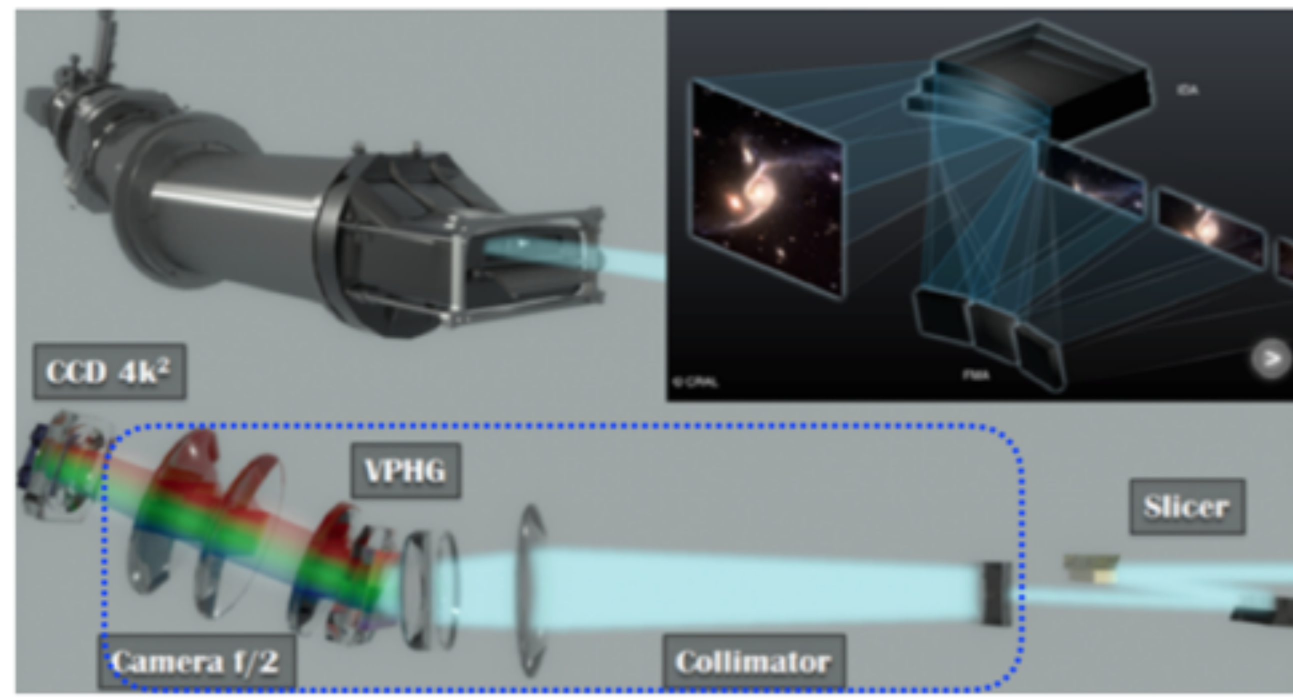


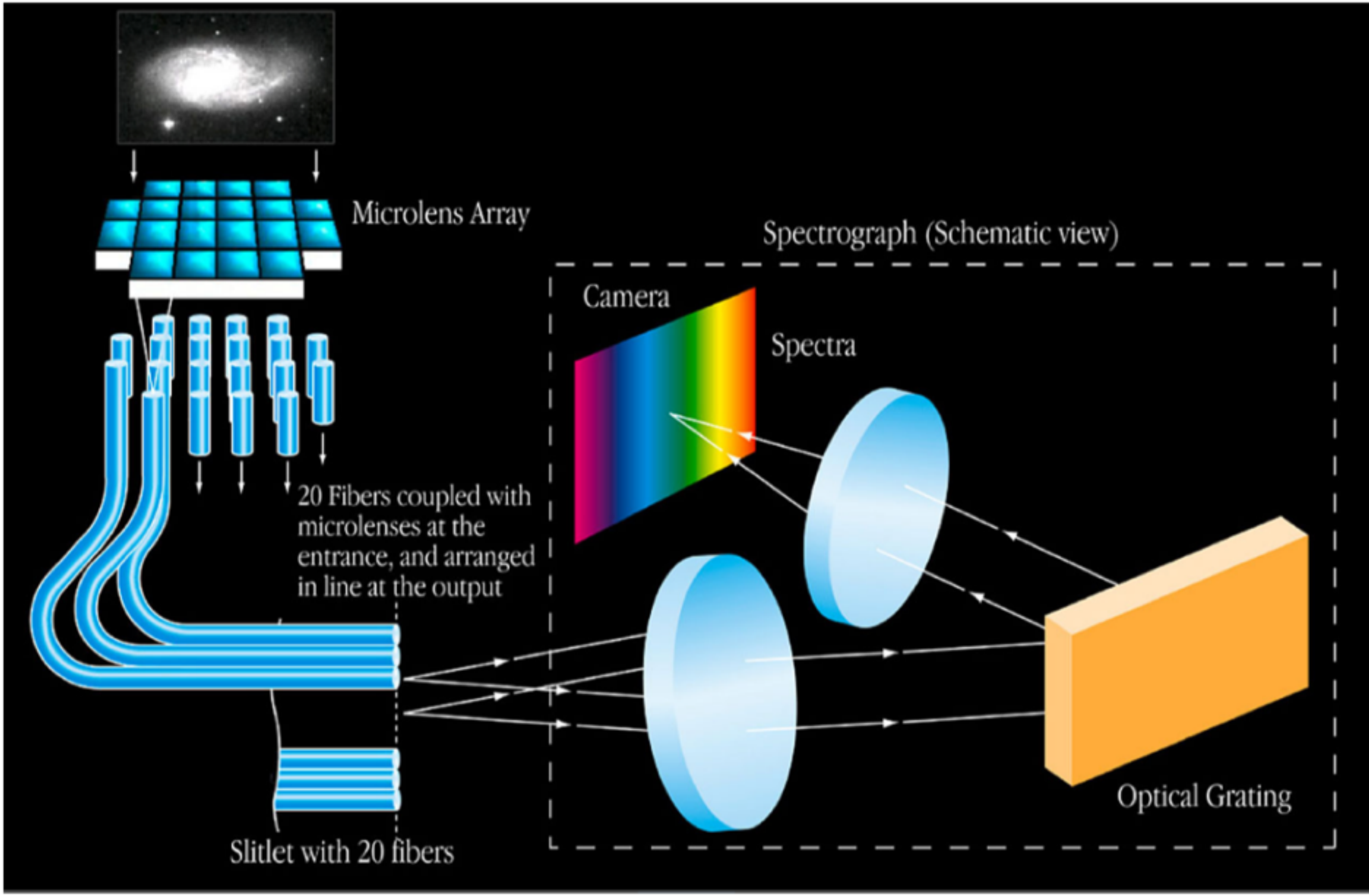
Figure 2.8. Schematic description of an Integral Field Unit (IFU) in the MUSE instrument. In dashed blue line is showing the spectrograph components. [39]

---

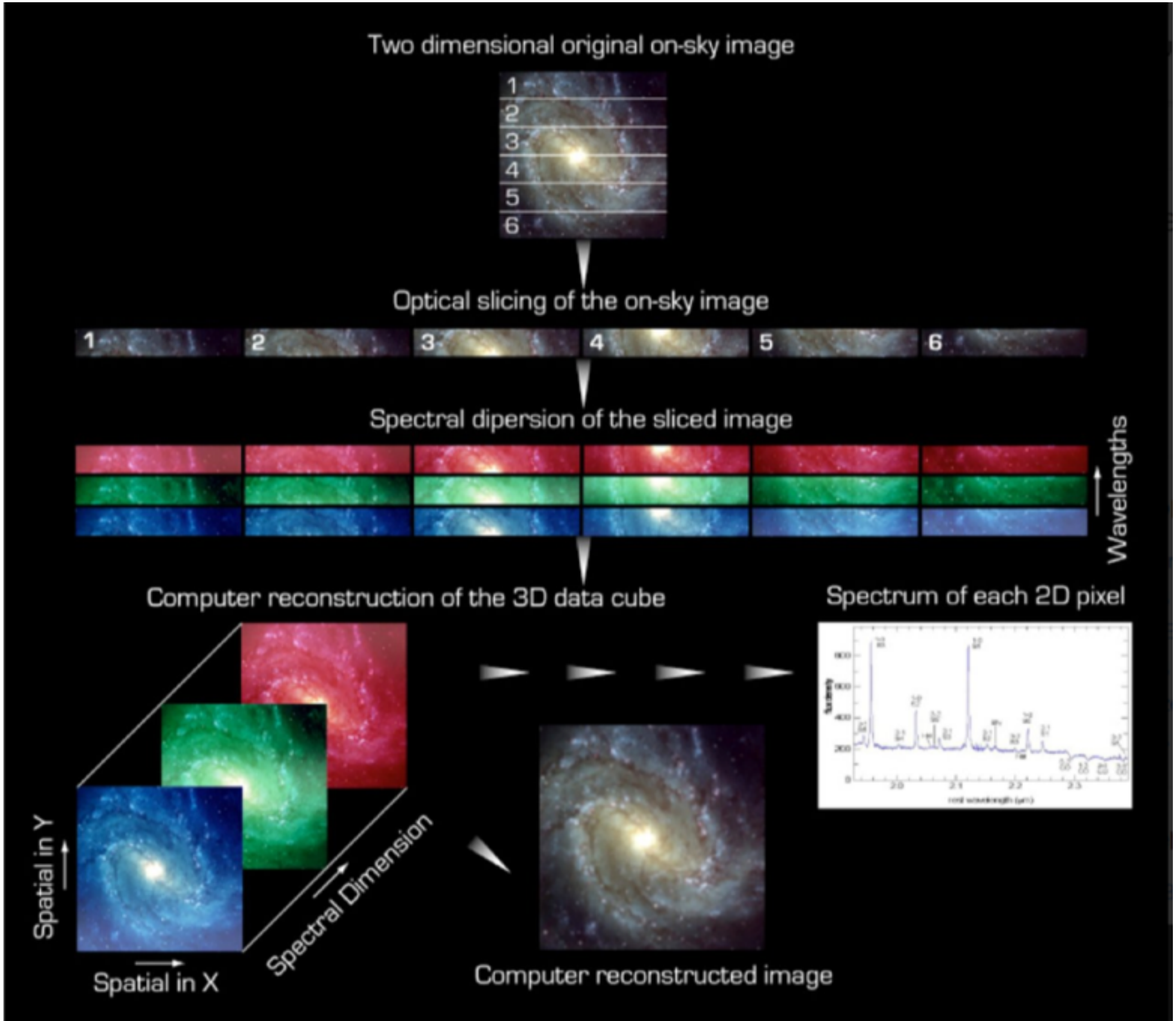
[5] Composed of a collimator, a Volume Phase Holographic Grating-VPHG (KOSI) [240] and, a Camera $\frac{f}{2}$ [39]

[6] The detectors used are deep depletion CCD231-84 (e2v) with 4096x4112 active 15 μm pixels. [241]

[7] In Wide Field Mode (WFM), MUSE splits a field of 1 $arcmin^2$ into 24 channels wich are further sliced into 48 minislits. [39]



(a) Operation of IFU, image taken from ESO[20]



(b) The Principle of Integral Field Spectroscopy (IFS) image-slicing [20]

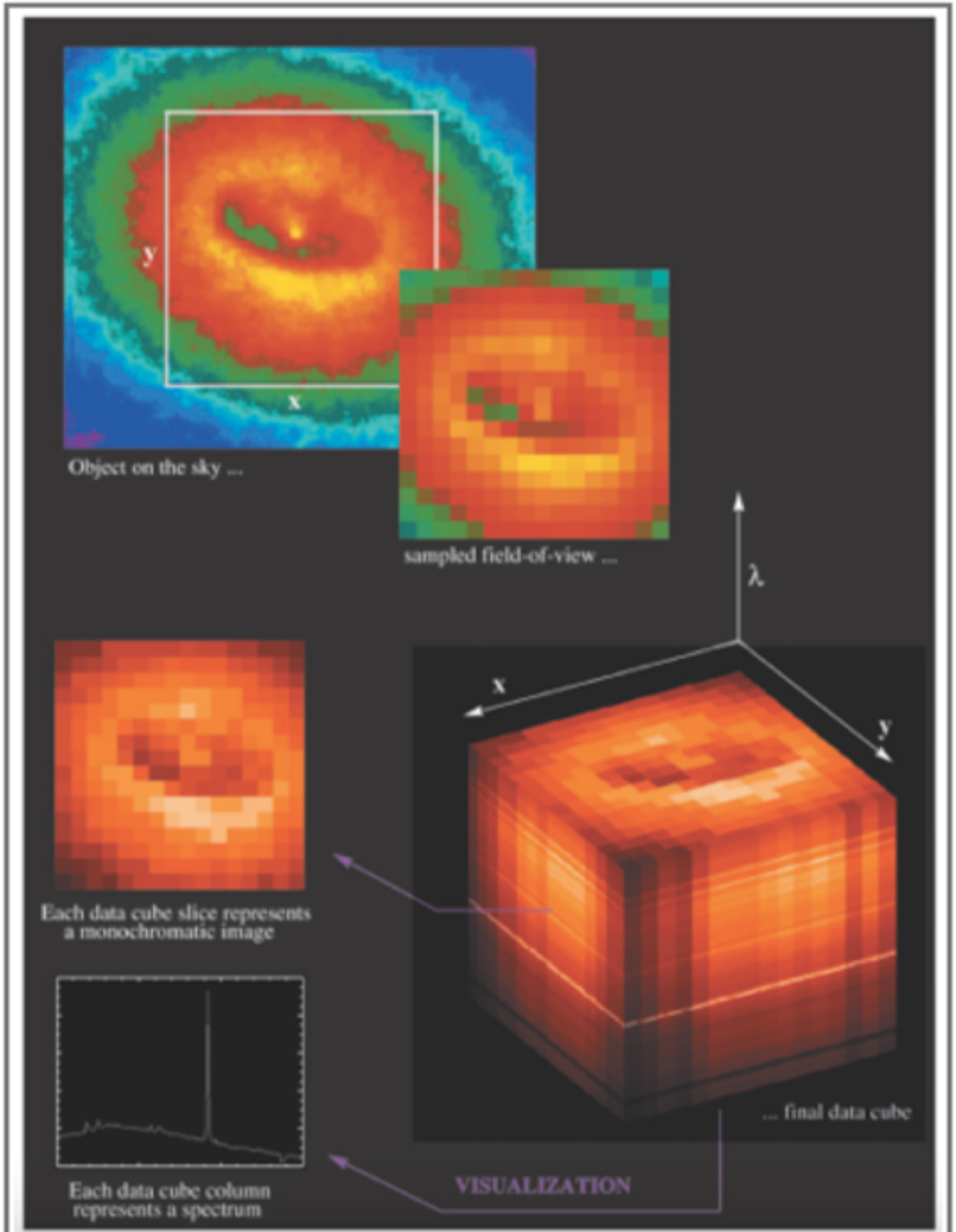


Figure 3: Description of the Data Cubes in IFS. [46]

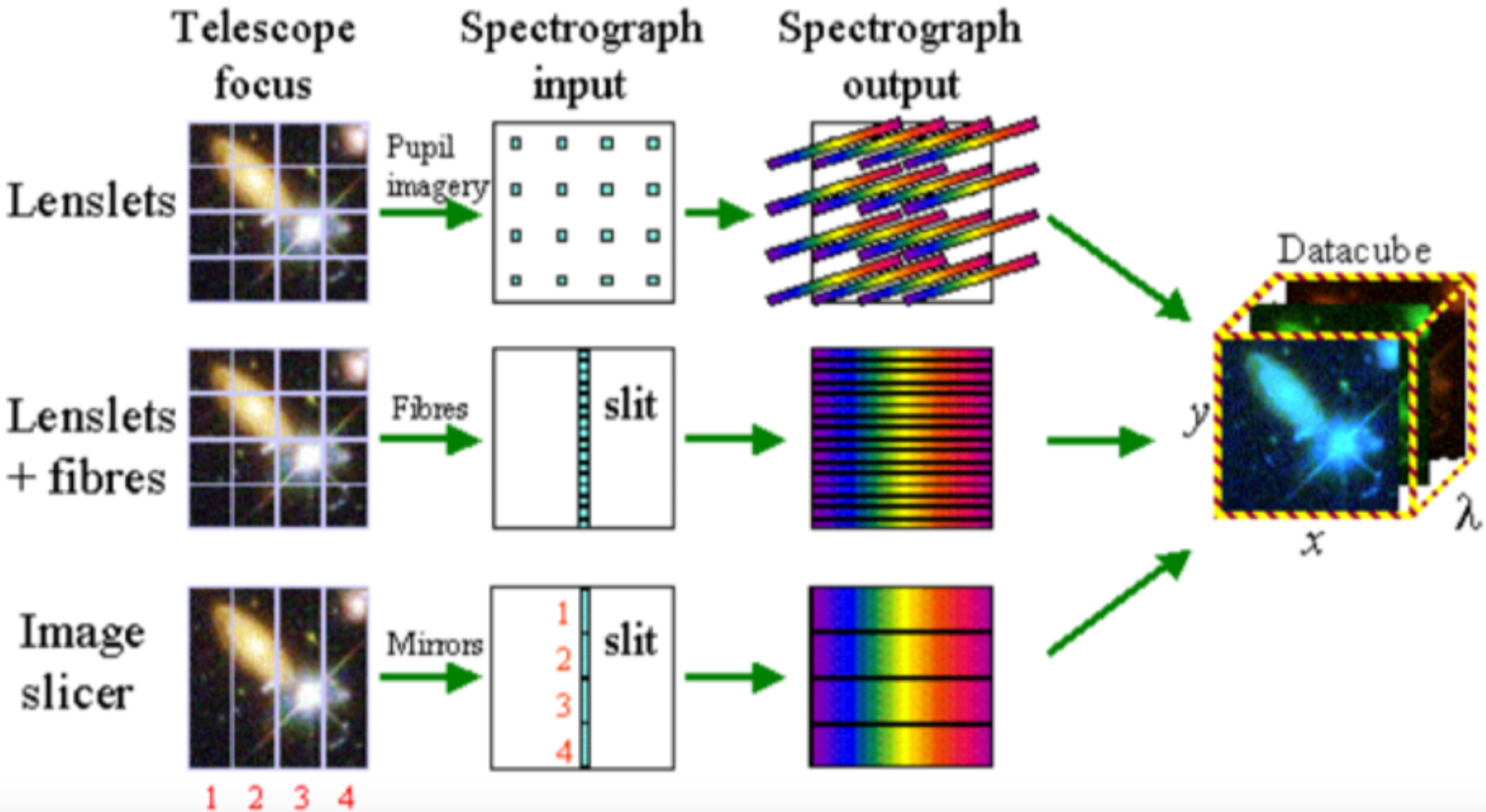


Figure 4: Schematic of the three main types of integral field spectrographs [34].

Facility/Instrument	First light	Aperture (M1 in m)	Field of View (sq. arcmin)	Wavelength coverage (μm)	Spectral resolution	Spatial sampling (arcsec²)	AO	Dedicated facility
GMT/GMTIFS	2030+	25	0.07x0.04	0.9-2.5	5000-10000	0.05x0.05	Yes	No
			0.04x0.02			0.025x0.025		
			0.02x0.01			0.012x0.012		
			0.01x0.005			0.006x0.006		
TMT/IRIS	2030+	30	0.03x0.07	0.84-2.4	4000-8000-10000	0.05x0.05	Yes	No
			0.02x0.04			0.025x0.025		
			0.02x0.02			0.009x0.009		
			0.01x0.01			0.004x0.004		
ELT/HARMONI	2030+	39	0.152x0.102	0.47-2.45	3500	0.06x0.03	Yes	No
			0.051x0.068			0.02x0.02		
			0.025x0.034	windows	3500-7500-18000	0.01x0.01		
			0.010x0.014			0.004x0.004		
GTC/MEGARA	2017	10.4	0.21x0.19	0.37-0.97	5500-12000-20000	0.62x0.62	No	No
Keck/KCWI	2017	10	0.55x0.34	0.35-1.08	1000-20000	1.38x1.38	No	No
			0.275x0.34			0.69x0.69		
			0.14x0.34			0.35x0.35		
VLT/MUSE	2014	8.2	1x1	0.46-0.93	2000-4000	0.2x0.2	Yes	No
			0.125x0.125			0.025x0.025	Yes	
VLT/BlueMUSE	2030+	8.2	1x1	0.35-0.60	4000	0.3x0.2	No	No
WHT/WEAVE	2022	4	20x0.02	0.37-1.00	5000	1.3	No	Yes
			1.5x1.3			2.6		
HET/HETDEX	2017	11	78x(0.85x0.85)	0.35-0.55	750-950	1.5	No	Yes
WST	2030+	12	9	0.37-0.97	3500	0.25x0.25	No	Yes

Figure 6: Information of current and upcoming Integral Field Spectrographs [29].

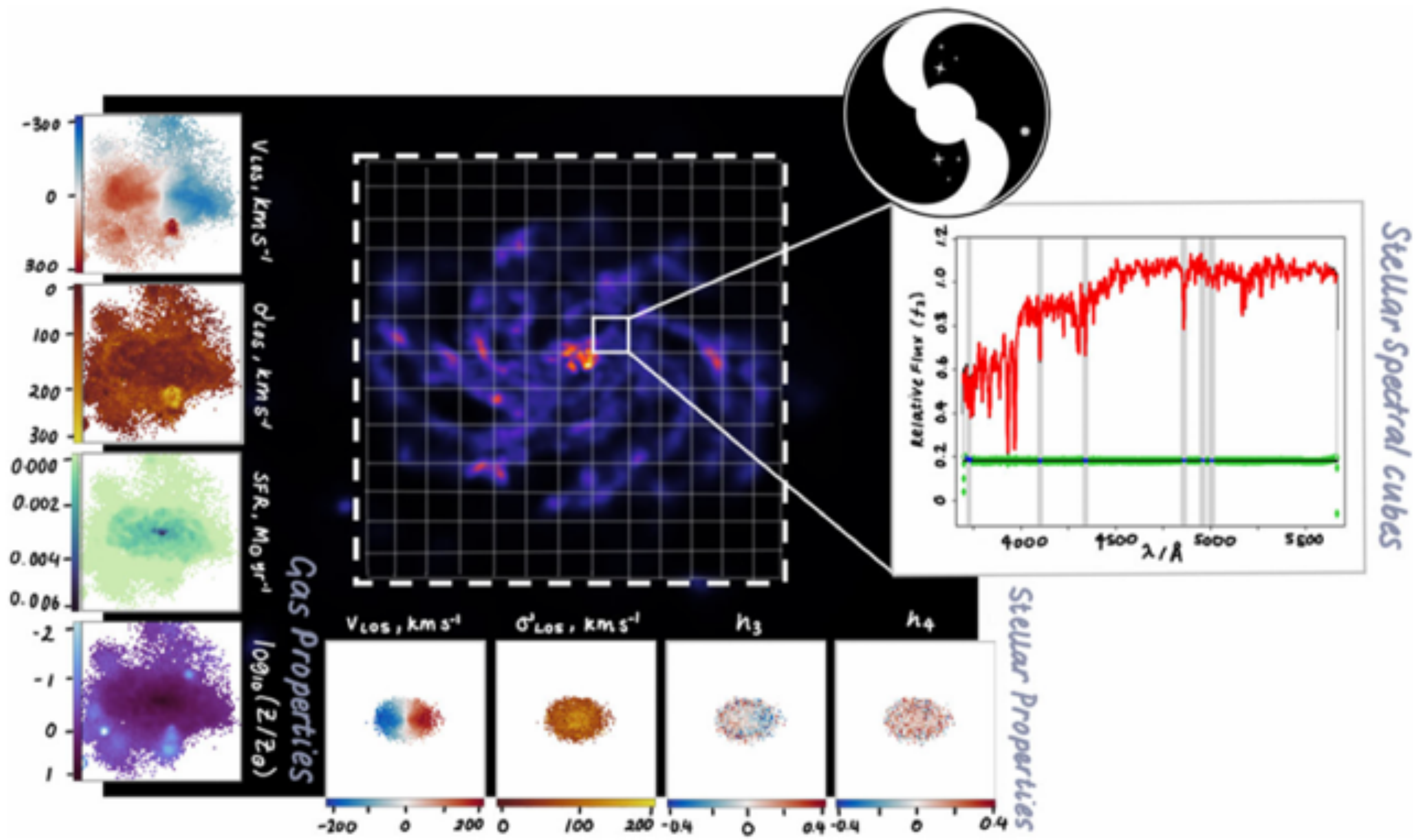
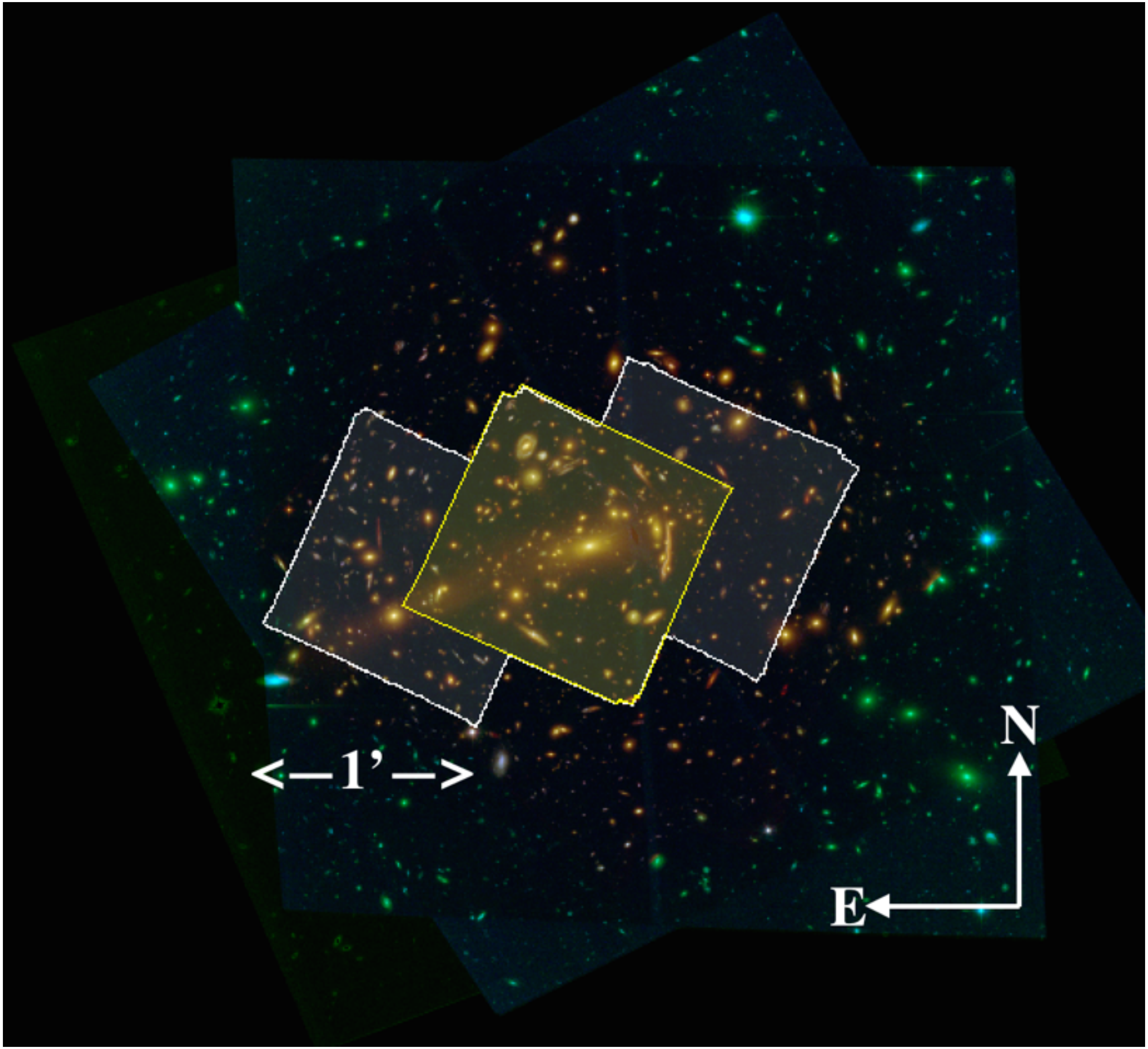
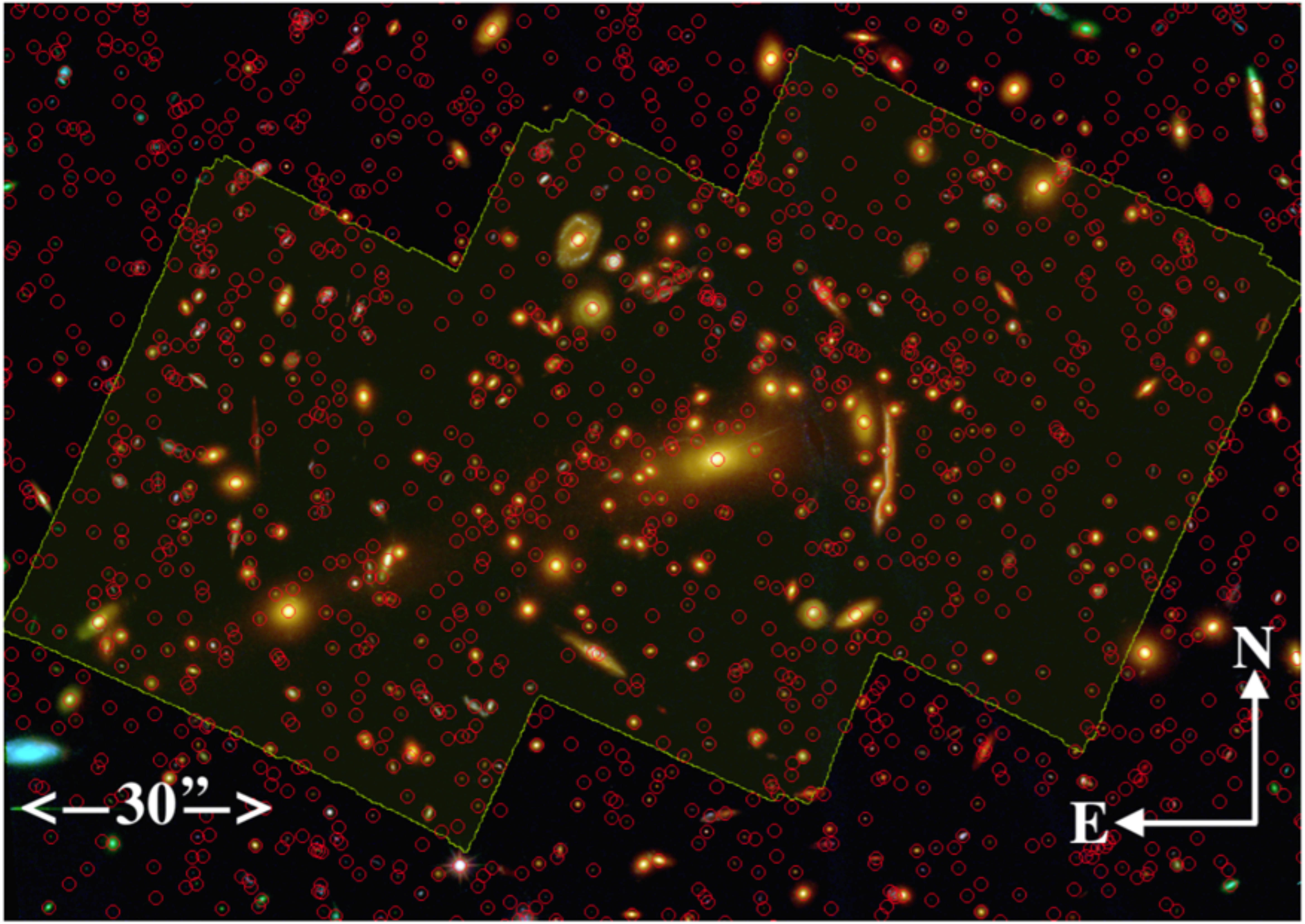


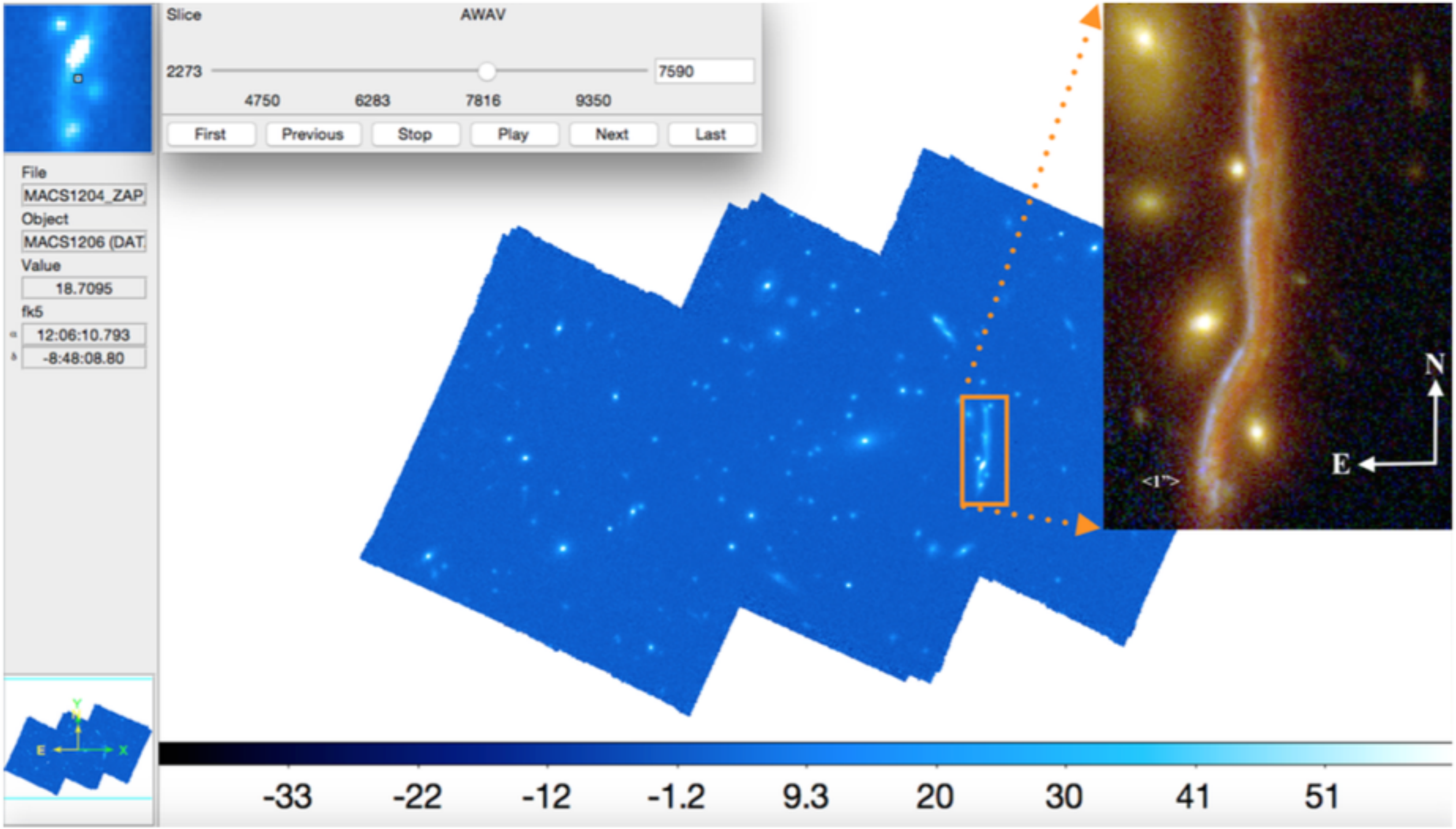
Figure 7: Recreation of possible spectrum outputs of a simulated galaxy using SimSpin. Taken from the article by K.E. Harborne et al [18] .



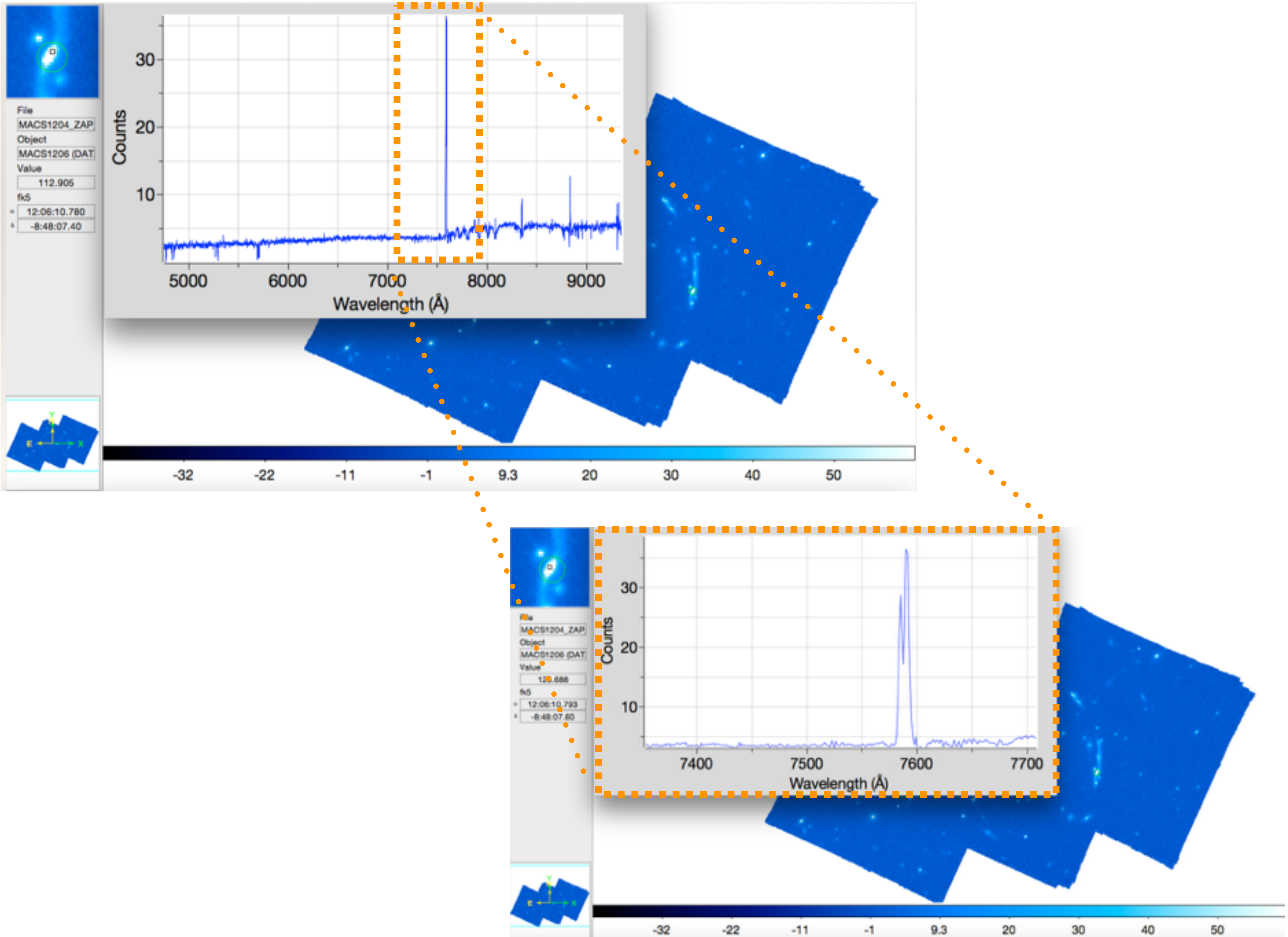
<—1'—>
N
E



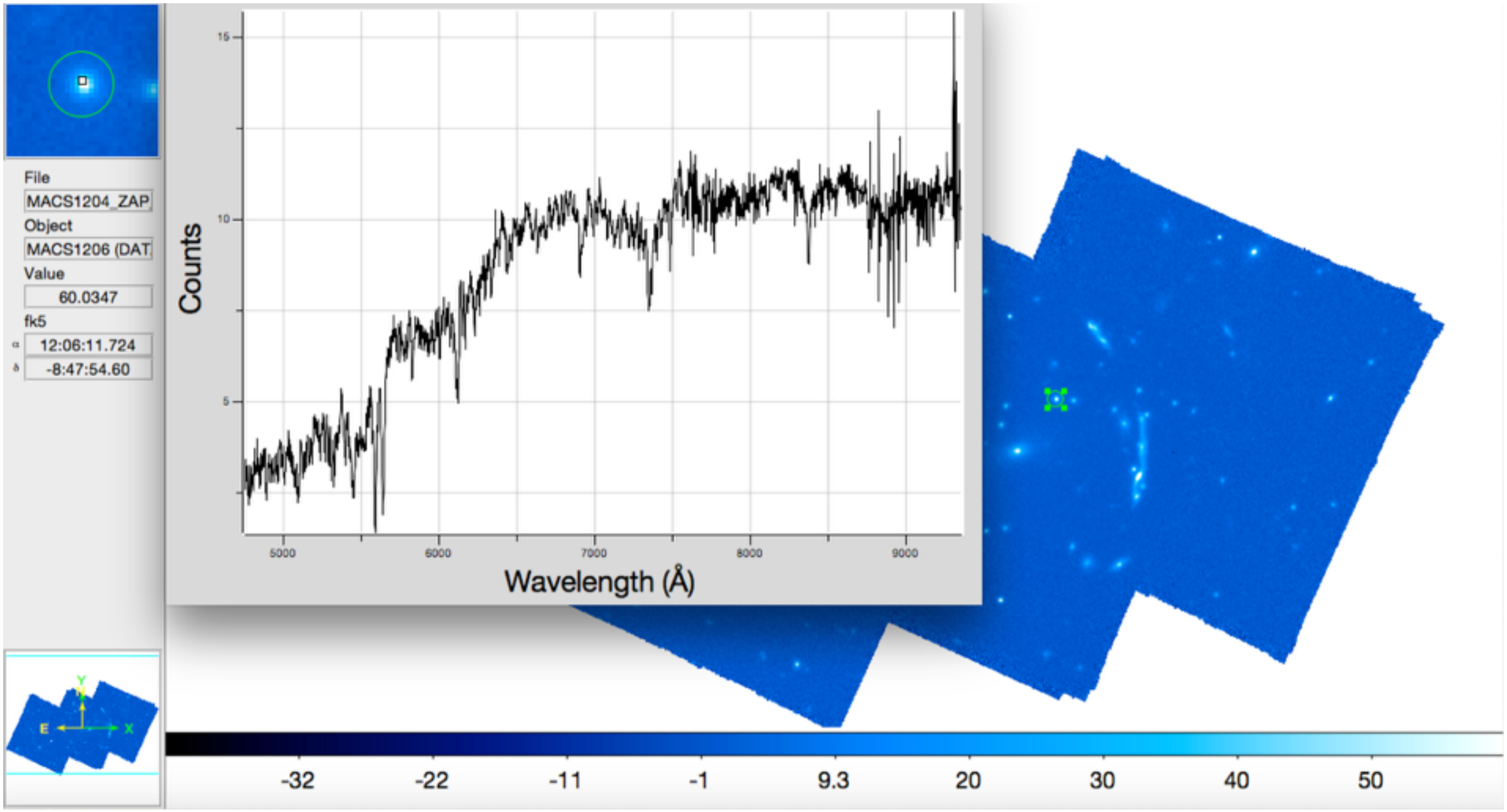
HST photometric identified objects (834) in the MUSE FoV of MACS 1206.

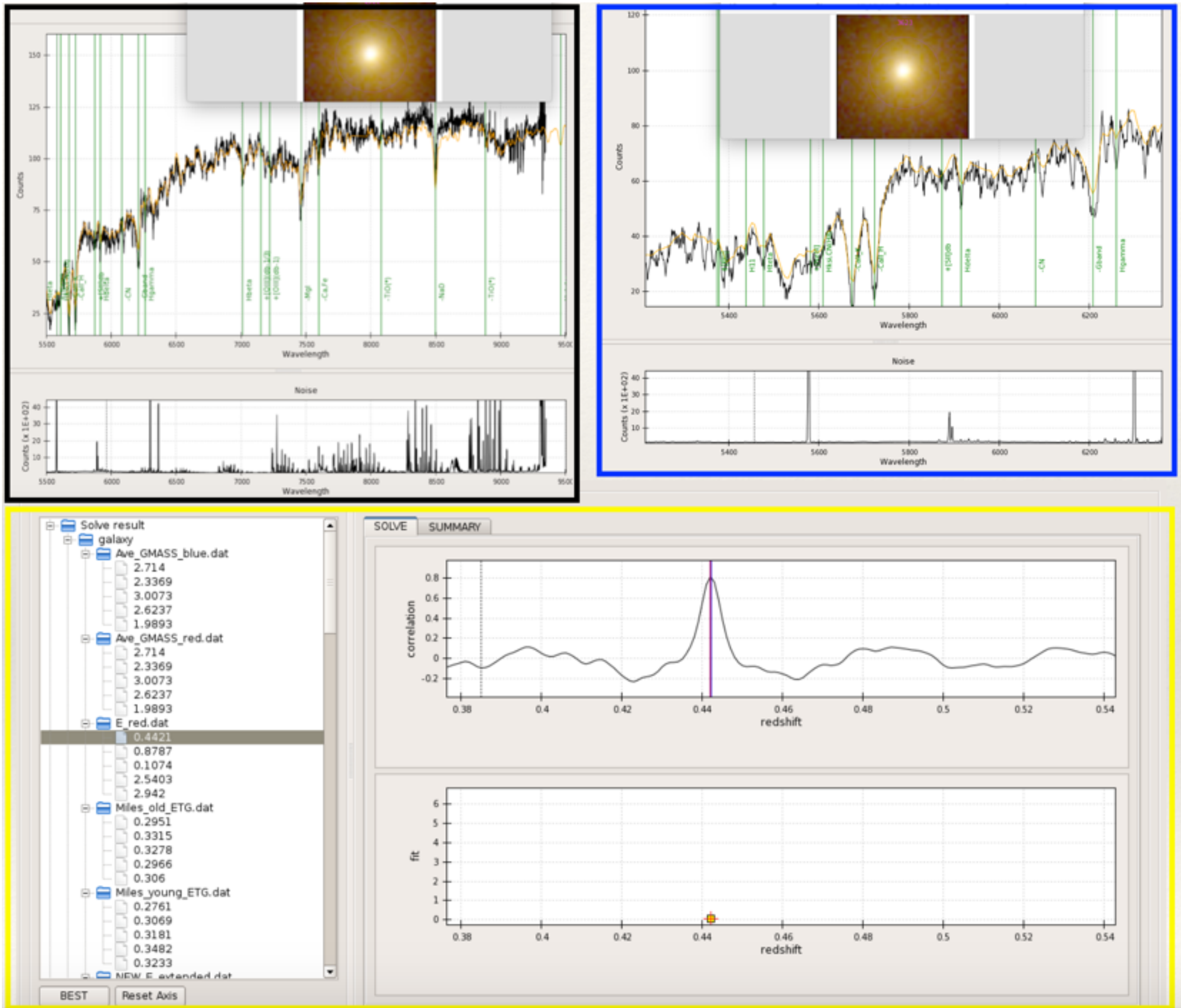


ds9 visualization of composed datacube of MUSE-VLT observations of MACS 1206.The image correspond to the dataplane at $\lambda_{observed} = 7590$Å that correspond to an $[OII]$ emission line ($\lambda_{emitted} = 3729.1$Å) at $z = 1.0353$. The RGB image at right top, is a zoom of the color composite HST image of 12 filters of MACS 1206



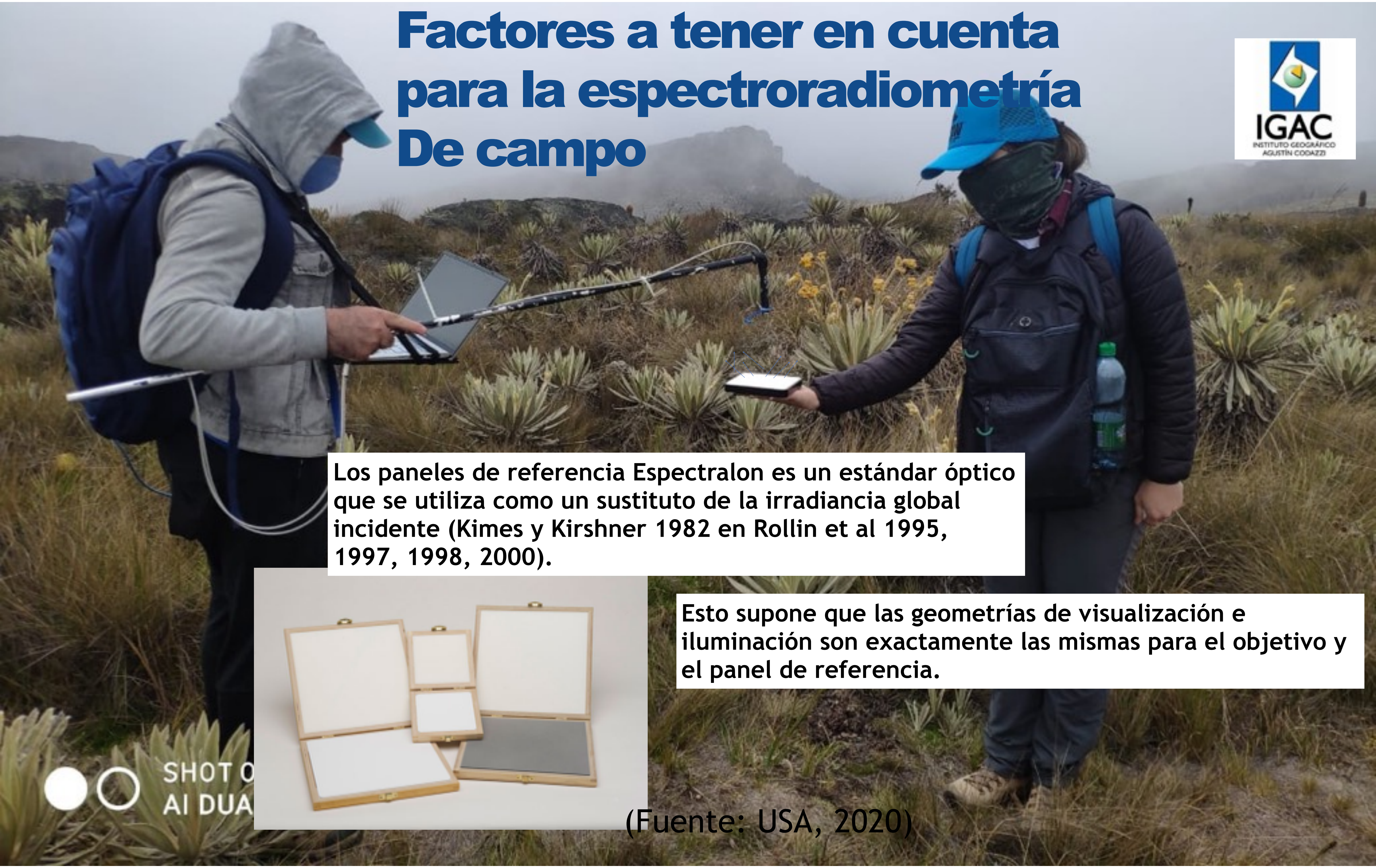
File
MACS1204_ZAP
Object
MACS1206 (DAT
Value
112.905
fk5
12:06:10.780
-8:48:07.40
Counts
30
20
10
5000
6000
7000
8000
9000
Wavelength (Å)
-32
-22
-11
-1
9.3
20
30
40
50
Counts
30
20
10
7400
7500
7600
7700
Wavelength (Å)


File
MACS1204_ZAP
Object
MACS1206 (DAT
Value
60.0347
fk5
12:06:11.724
-8:47:54.60
Counts
15
10
5
5000
6000
7000
8000
9000
Wavelength (Å)
-32
-22
-11
-1
9.3
20
30
40
50



Counts
Wavelength
Noise
Counts (x 1E+02)
Solve result
galaxy
Ave_GMASS_blue.dat
2.714
2.3369
3.0073
2.6237
1.9893
Ave_GMASS_red.dat
2.714
2.3369
3.0073
2.6237
1.9893
E_red.dat
0.4421
0.8787
0.1074
2.5403
2.942
Miles_old_ETG.dat
0.2951
0.3315
0.3278
0.2966
0.306
Miles_young_ETG.dat
0.2761
0.3069
0.3181
0.3482
0.3233
BEST
Reset Axis
SOLVE
SUMMARY
correlation
redshift
fit
redshift

Espectroradiometría



Factores a tener en cuenta para la espectroradiometría De campo

Los paneles de referencia Espectralon es un estándar óptico que se utiliza como un sustituto de la irradiancia global incidente (Kimes y Kirshner 1982 en Rollin et al 1995, 1997, 1998, 2000).

Esto supone que las geometrías de visualización e iluminación son exactamente las mismas para el objetivo y el panel de referencia.

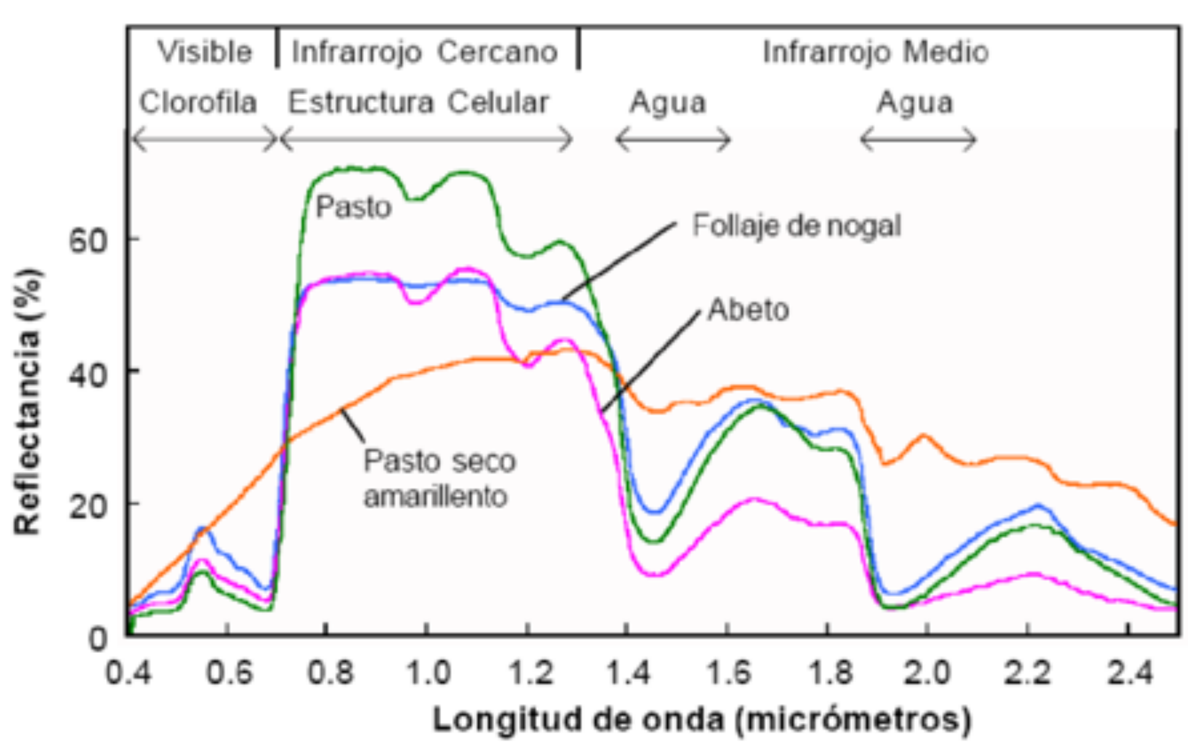
(Fuente: USA, 2020)

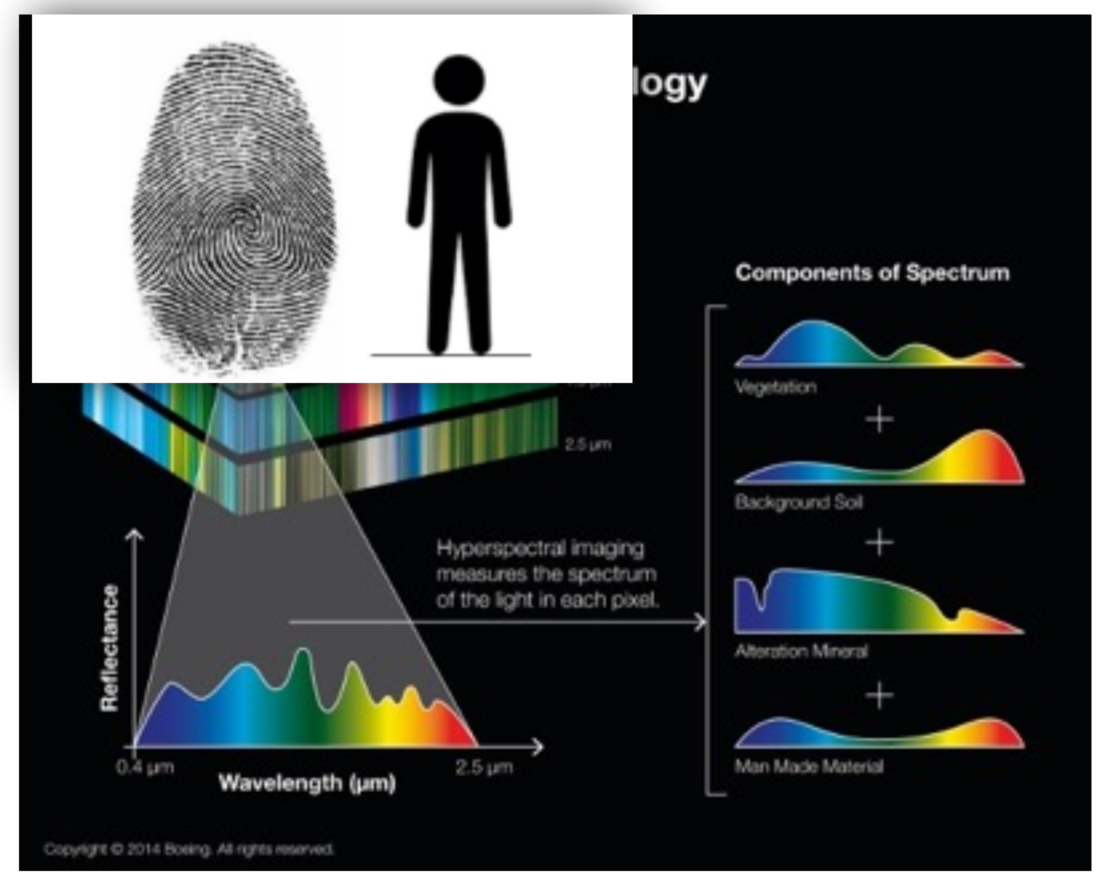
Fundamentos de Espectroradiometria

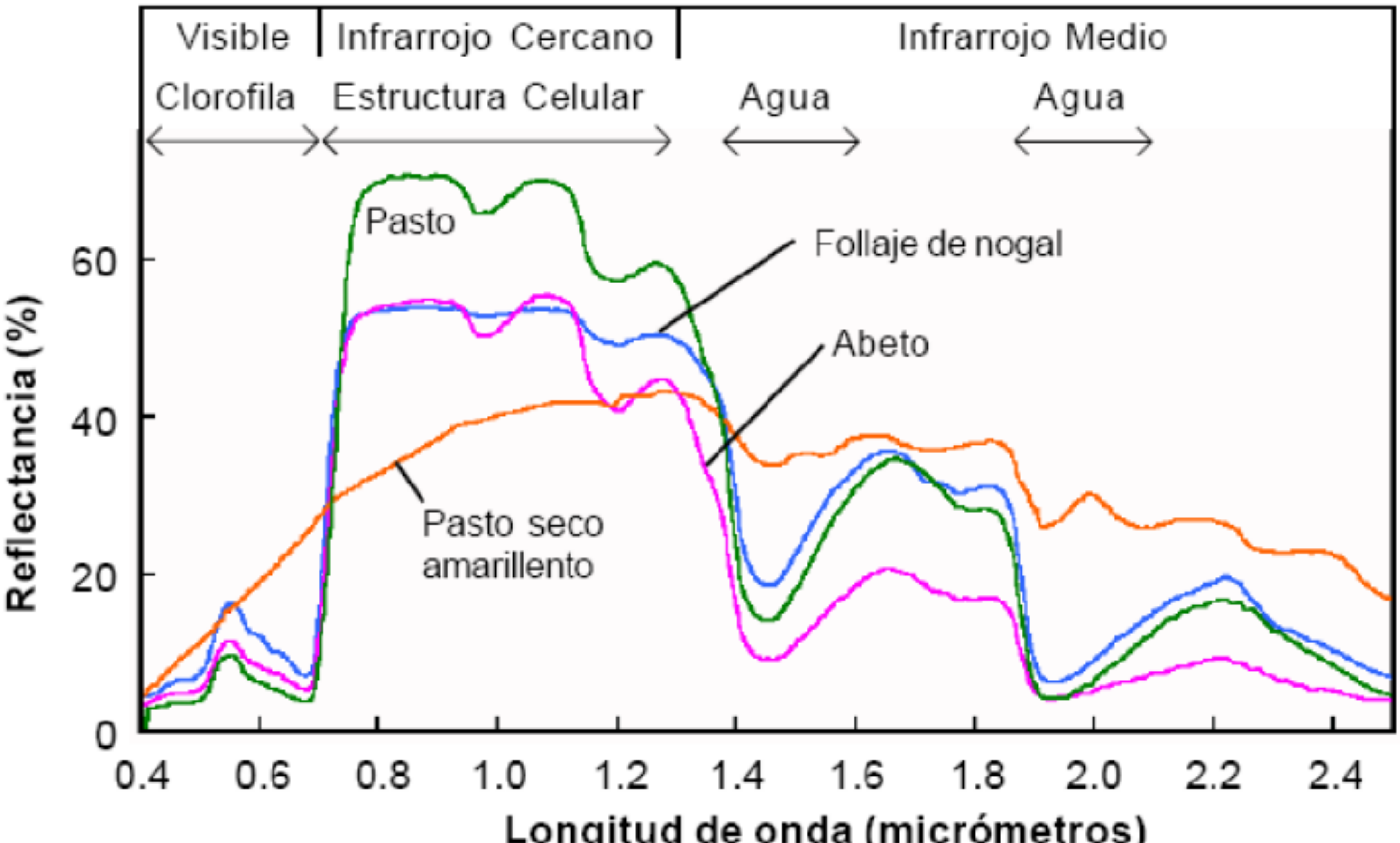
FIRMAS ESPECTRALES

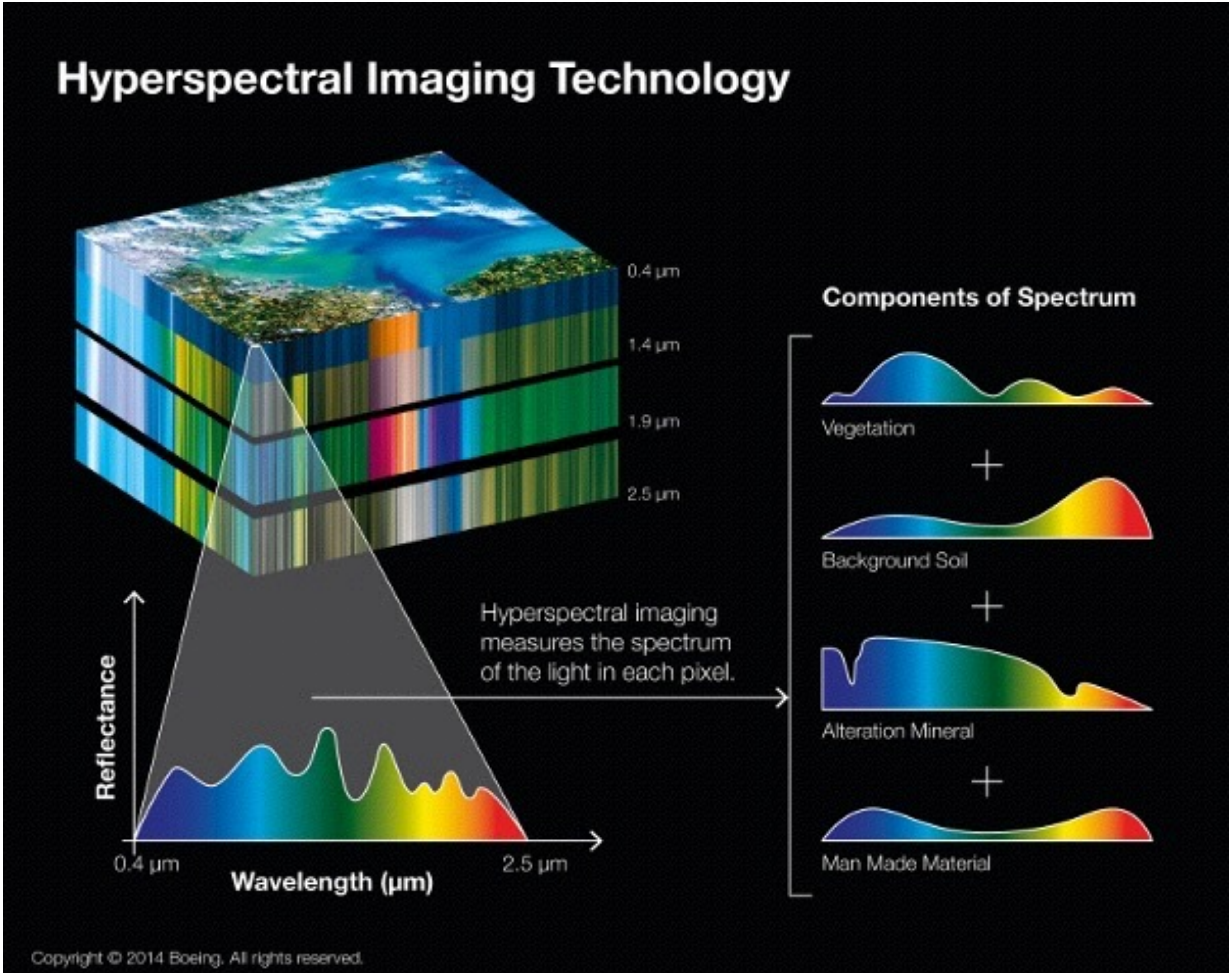
Firma espectral es la medida cuantitativa de las propiedades espectrales de un objeto en una o varias bandas espectrales. También se la conoce como comportamiento espectral

Cada tipo de objeto presenta a un nivel de respuesta específico en términos de proporción : % radiación reflejada + % absorbida + % transmitida



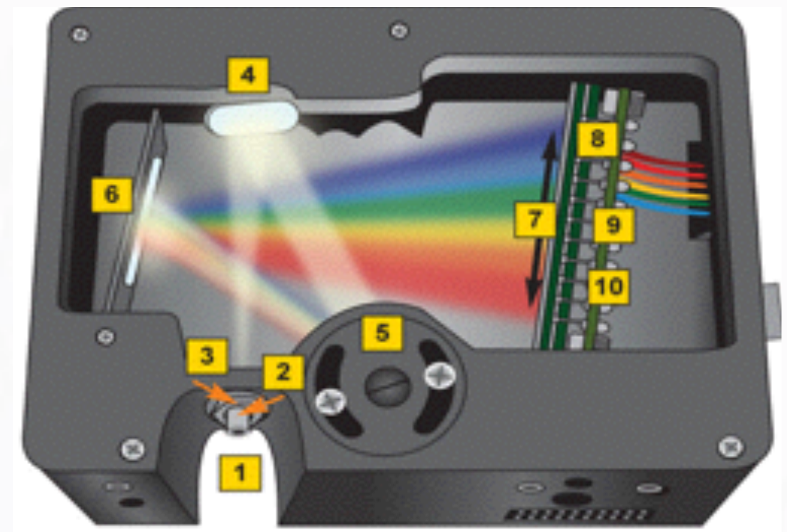



Visible
Infrarrojo Cercano
Infrarrojo Medio
Clorofila
Estructura Celular
Agua
Agua
Pasto
Follaje de nogal
Abeto
Pasto seco amarillento
Reflectancia (%)
0
20
40
60
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Longitud de onda (micrómetros)


Hyperspectral Imaging Technology
0.4 µm
1.4 µm
1.9 µm
2.5 µm
Components of Spectrum
Vegetation
Background Soil
Alteration Mineral
Man Made Material
Hyperspectral imaging measures the spectrum of the light in each pixel.
Reflectance
0.4 µm
2.5 µm
Wavelength (µm)
Copyright © 2014 Boeing. All rights reserved.

1.3. Equipos del Laboratorio

- ¿ESPECTROMETRO ÓPTICO? es un instrumento que sirve para medir las propiedades de la luz en una determinada porción del espectro electromagnético.

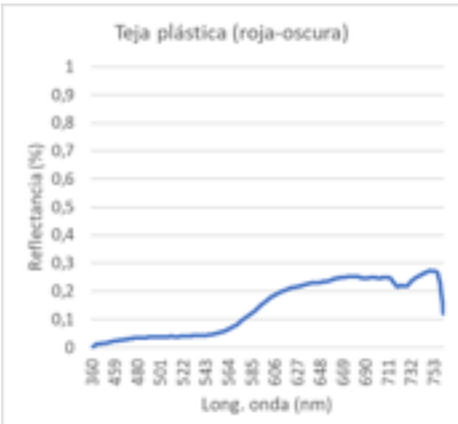


ASD FieldSpec® 4 Hi-Res: espectroradiómetro de alta resolución

Resolución SWIR de 8 nm ideal para estudios geológicos e investigación atmosférica

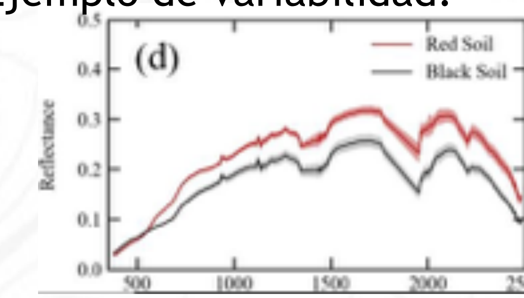
El ASD FieldSpec® 4 Hi-Res es un espectroradiómetro de alta resolución diseñado para mediciones de datos espectrales más rápidas y precisas para una amplia gama de aplicaciones de detección remota.

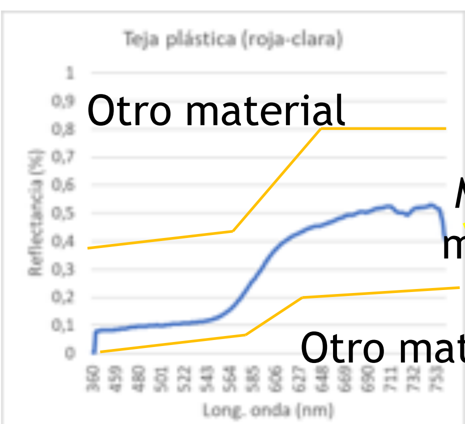
Planteamiento del problema



Firma remuestreada (RGBN):

Ejemplo de variabilidad:



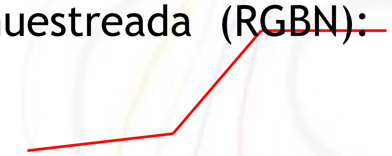


Otro material

Mismo material

Otro material

Firma remuestreada (RGBN):



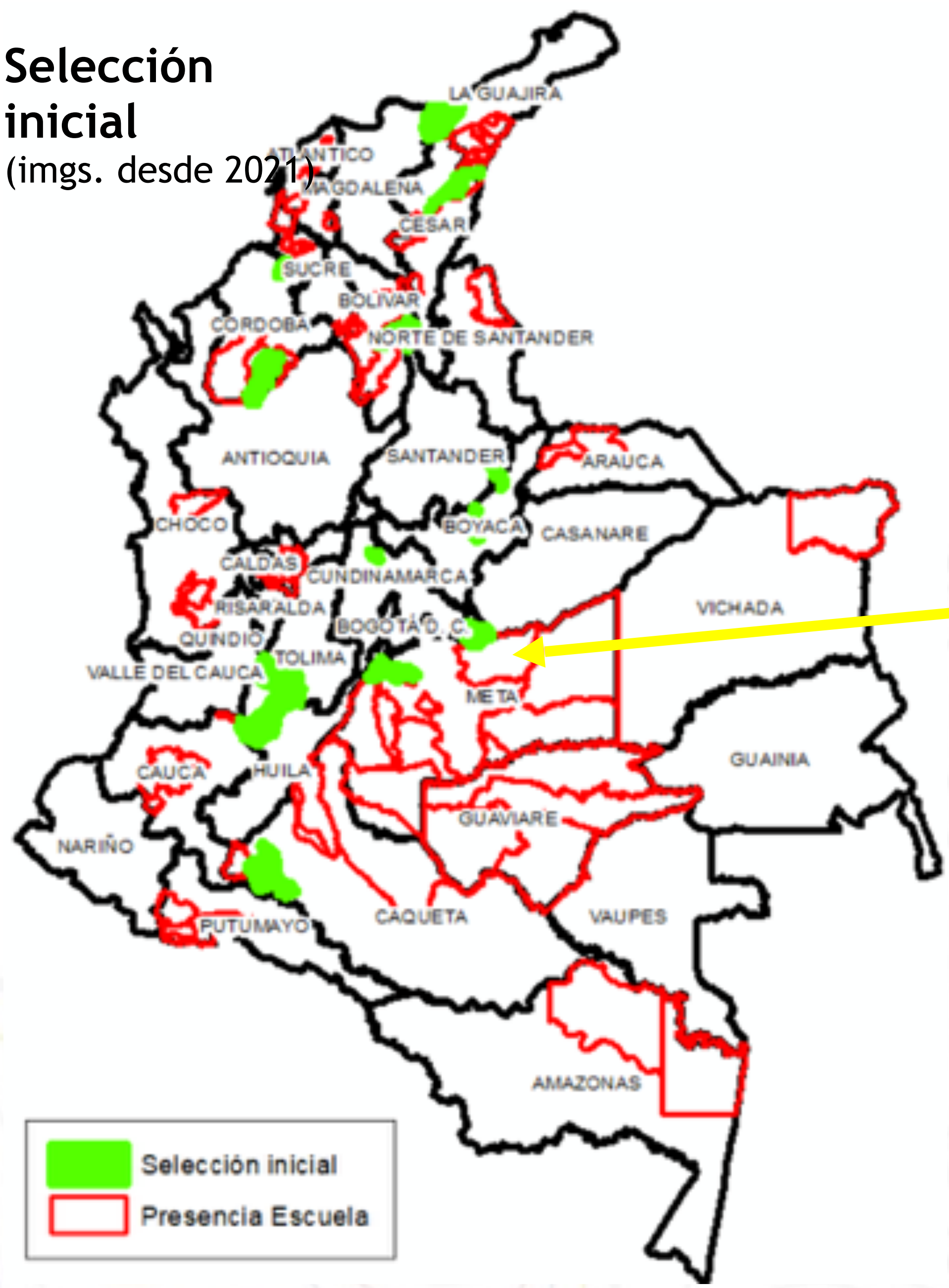
Variabilidad espectral

Gobierno de Colombia

IGAC Instituto Geográfico Agustín Codazzi

Zona de estudio

Selección inicial
(imgs. desde 2021)



Imágenes más recientes

Departamento	Mpio/centro poblado
Arauca	Arauquita
Córdoba	Valencia
Cundinamarca	San Juan De Rioseco
Guaviare	San José Del Guaviare
Huila	Aipe
Huila	Gigante
Meta	Cabuyaro
Meta	Cubarral
Meta	Puerto López
Tolima	Ataco

Ortoimagen Urbana. Municipio de Puerto López, Meta. Resolución 20 cm

Entidad: Instituto Geográfico Agustín Codazzi - IGAC

Resumen:

La ortoimagen del municipio de Puerto López (Meta), elaborada en el año 2023 por el Instituto Geográfico Agustín Codazzi (IGAC), es un producto compuesto de imágenes ortorrectificadas en el cual se han efectuado procesos de balance radiométrico y edición de líneas de costura para garantizar su continuidad. Generado a partir de imágenes capturadas con el sensor Vexcel Eagle Mark 3 en toma del 30 de junio de 2023, representa un área de 974.61 Ha cubriendo totalmente el centro poblado del municipio.

Nivel de detalle: 20 cm

Fecha: 20-10-2023

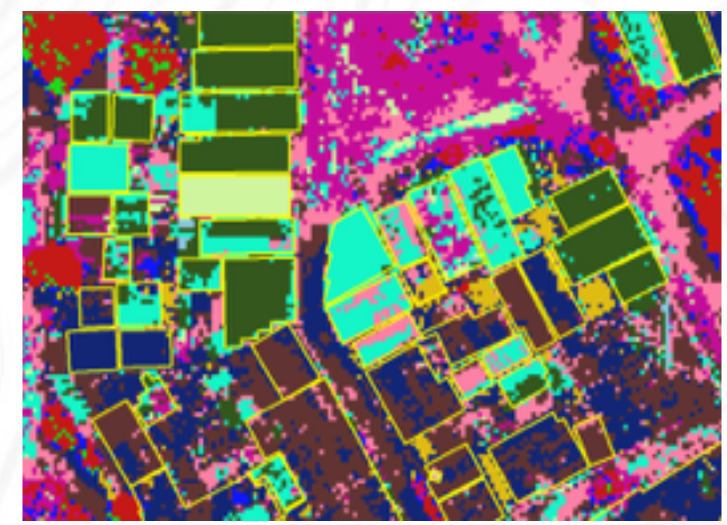
Licencia: CC BY 4.0

Diseño metodológico

Preprocesamiento
- Protocolo firmas
- Preparación imágenes: ortomosaicos, recortes, índices, remuestreo
- Muestreo campo
- Submuestreo cubierta

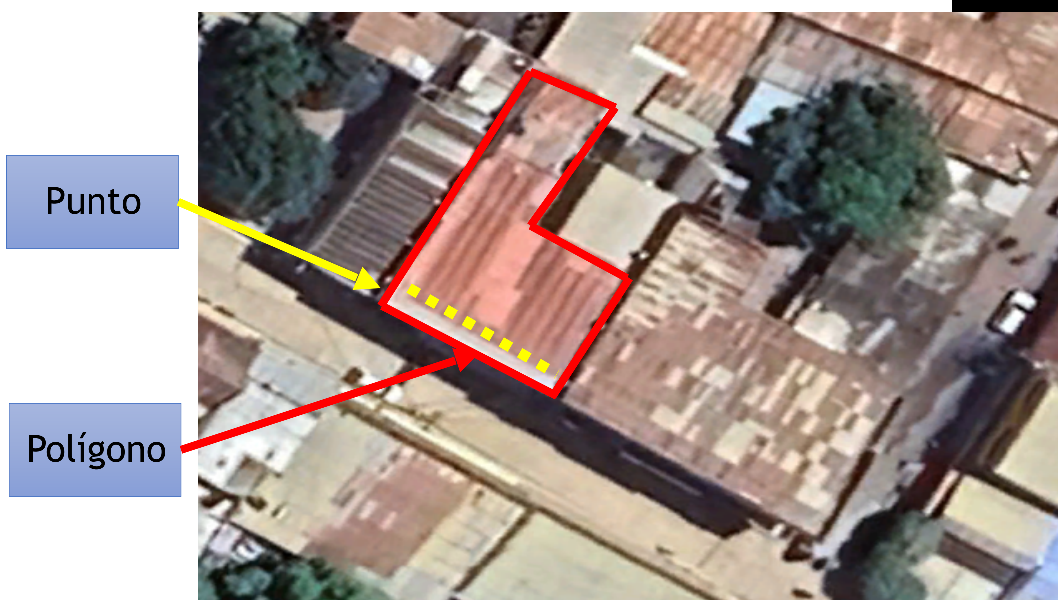
Procesamiento
- Firmas
  - Organización-depuración, etc. firmas
  - Creación librería espectral (LIB. ESP.)
  - Operaciones LIB. ESP.: derivadas, remoción continuo, índices, remuestreo, etc…
- Endmember: punto-polígono
- Imágenes
  - Corrección radiométrica (si aplica)
  - Clasificación imagen - cubiertas

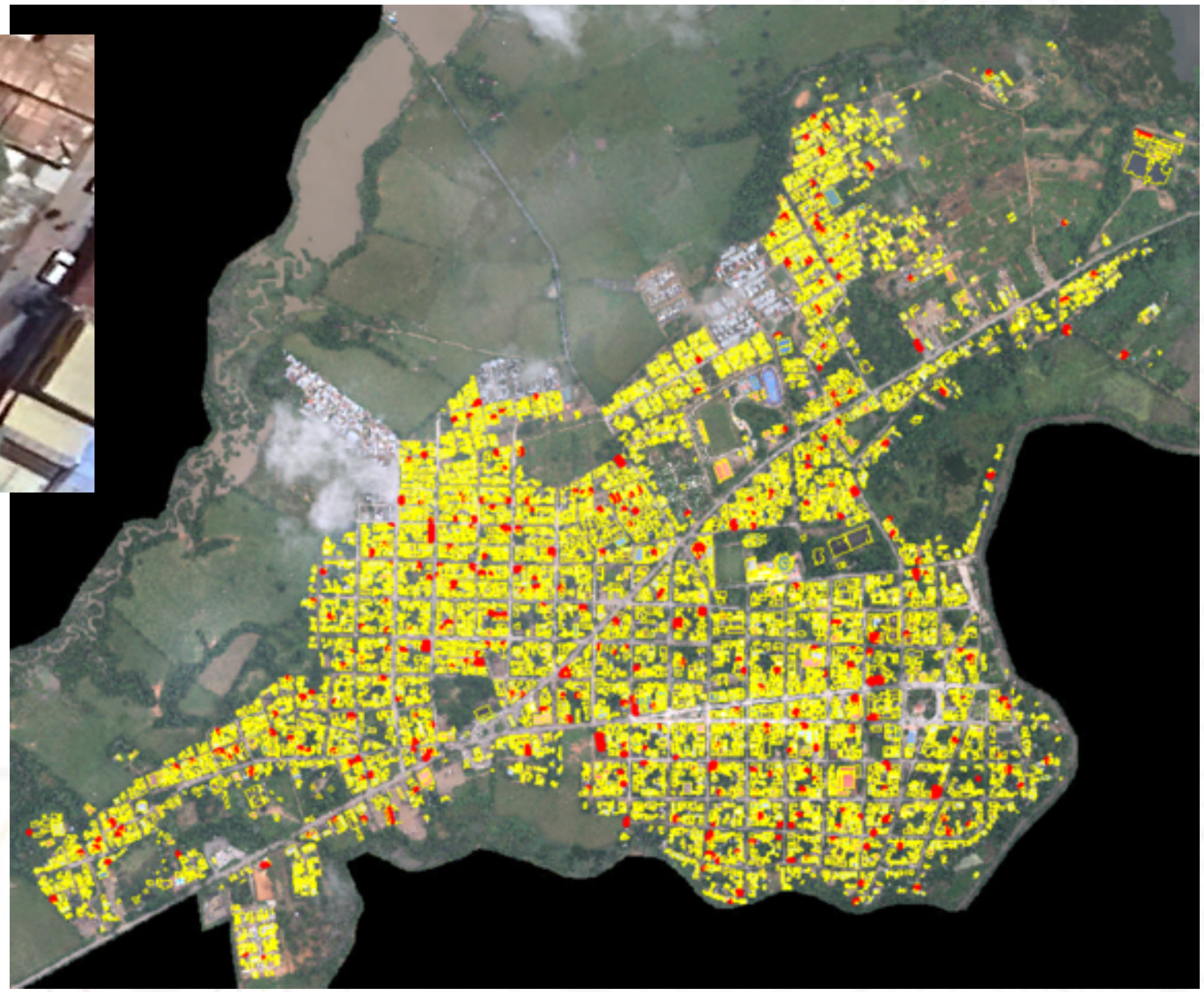
Posprocesamiento
- Validación
  - Análisis de resultados



Muestreo aleatorio estratificado: 331 cubiertas, distribuidas por clúster y variabilidad espectral interna.

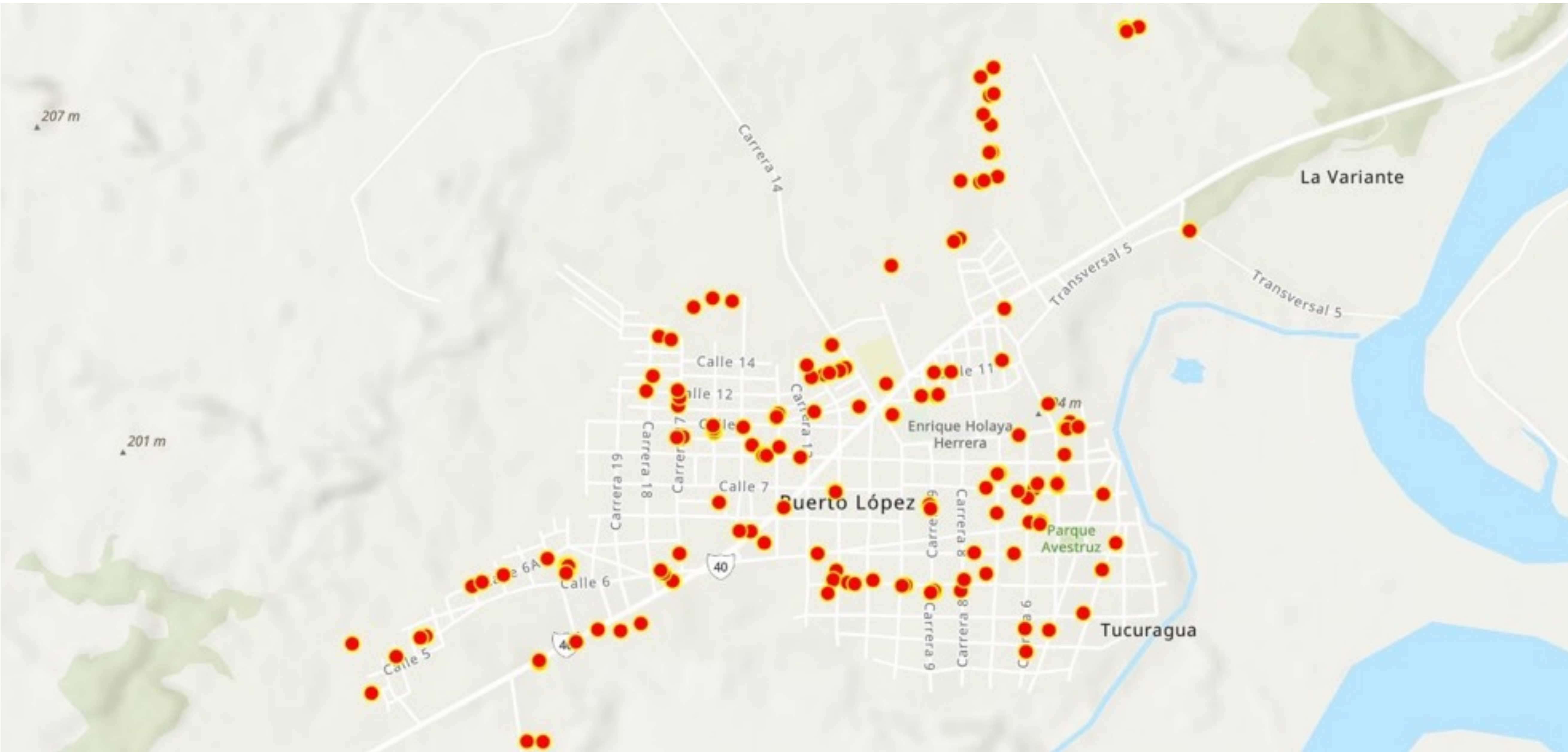
Muestreo-submuestreo (Puerto López, Meta)

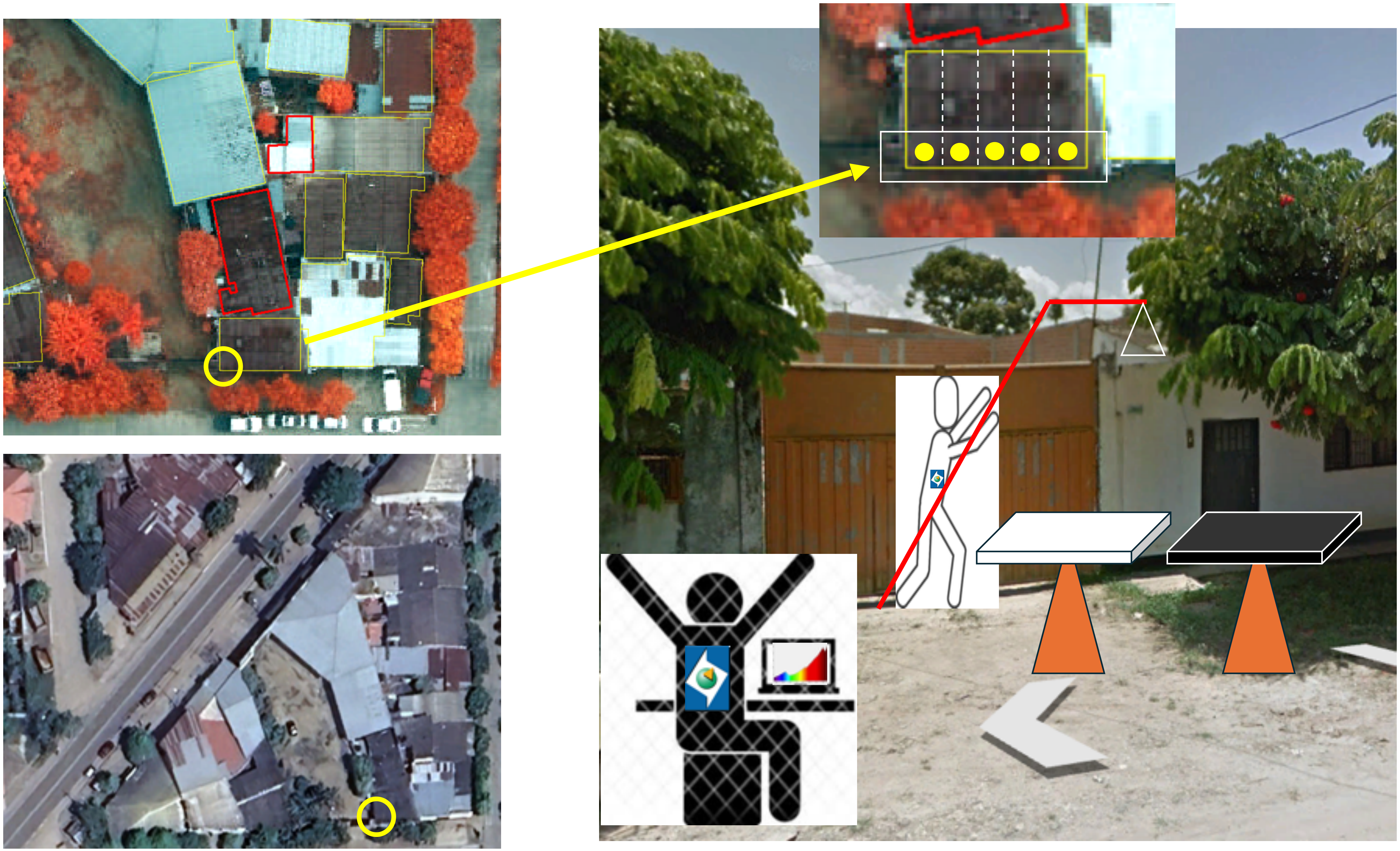


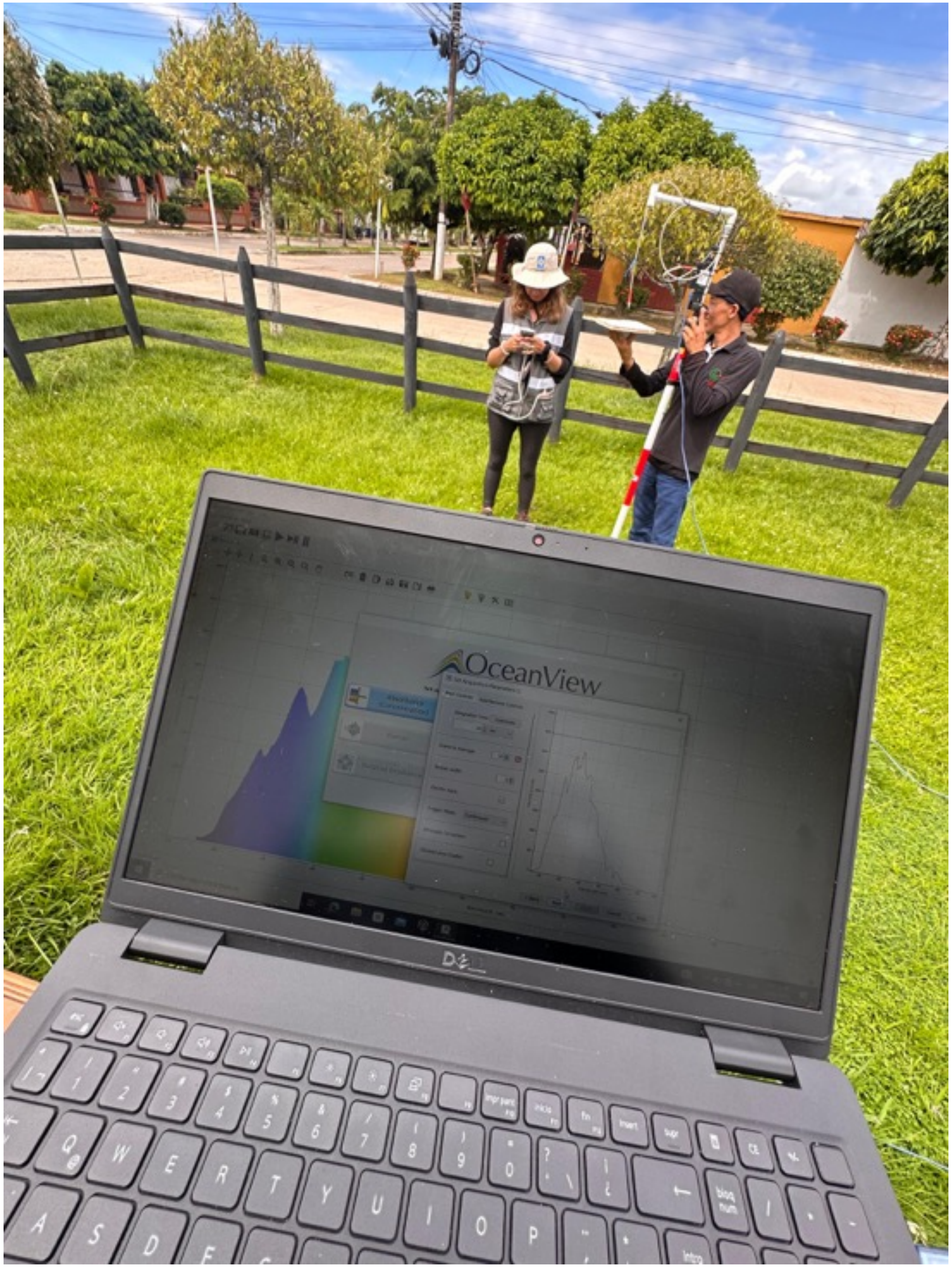


Clase	No.	Clase	No.
10_Q1	9	2_Q1	1
10_Q2	9	3_Q1	2
10_Q3	8	4_Q1	1
10_Q4	30	6_Q1	1
11_Q1	39	6_Q2	1
11_Q2	46	6_Q3	1
11_Q3	37	7_Q1	3
11_Q4	31	7_Q2	1
12_Q1	21	8_Q1	8
12_Q2	24	8_Q2	1
12_Q3	35	9_Q1	2
12_Q4	20	9_Q2	1
Total		**331**	

Medición de las firmas espectrales de Cubiertas en Puerto Lopez






OceanView


JJR-108
IGAC


IGAC


TopOne

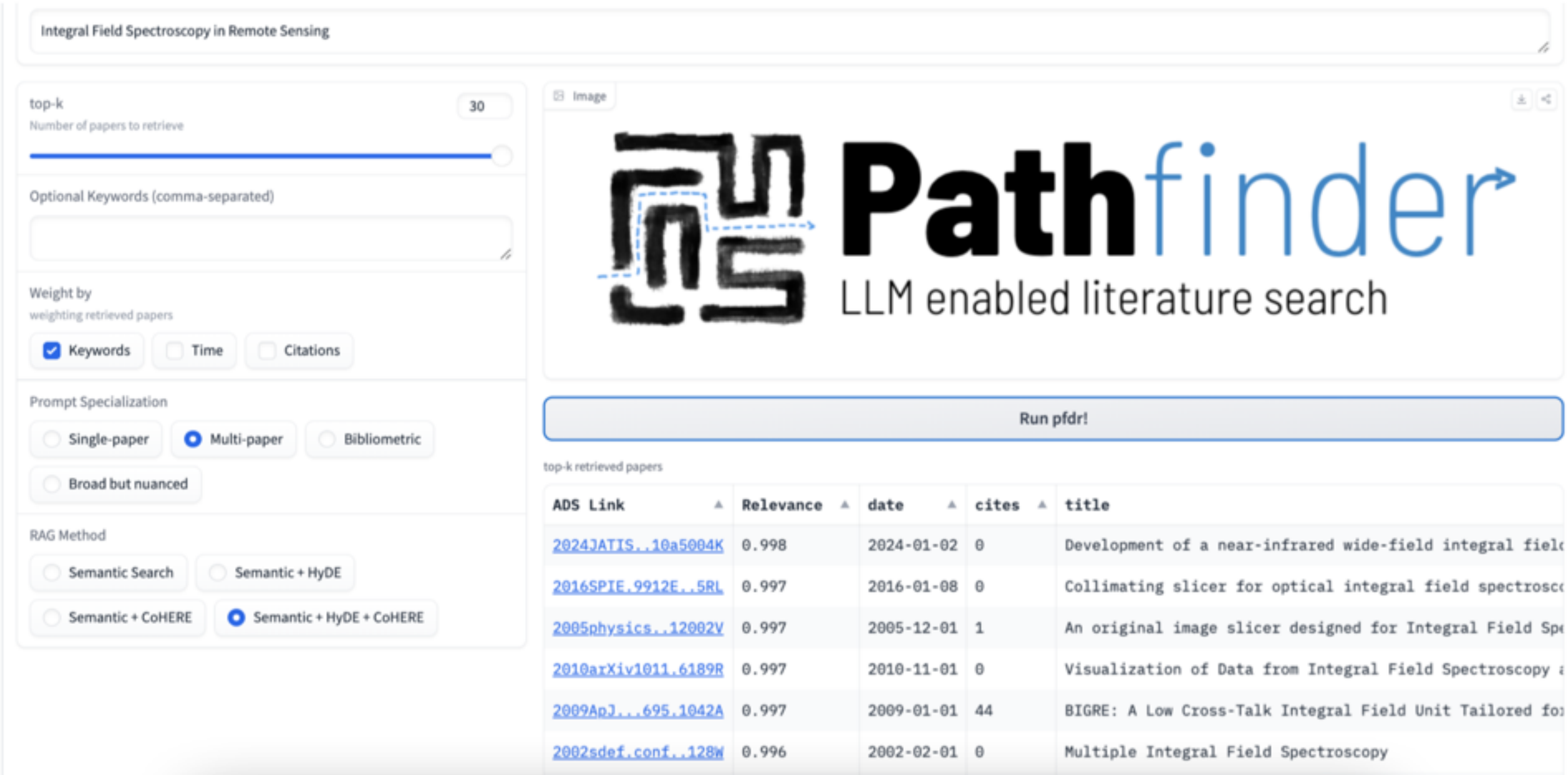


Figure 1: Large language models(LLM) Pathfinder tool, extracting data set papers for the prompt "Integral Field Spectroscopy in Remote Sensing" using Semantic- HyDe-CoHere methods.

IFS in Remote Sensing

IFS has diverse applications in remote sensing, including land cover classification, vegetation monitoring, atmospheric studies, and urban mapping and present advantages over traditional remote sensing techniques [31], such as its ability to capture fine spatial details, differentiate between spectrally similar materials, and characterize complex spectral signatures[35]. However, we also address challenges, including data volume, computational requirements, and instrument complexity, and it is necessary advancements in instrumentation, data processing algorithms, and integration with emerging technologies such as unmanned aerial vehicles (UAVs) and satellite constellations[5][22]. There is a potential for the utilization of these techniques in Earth observation range from monitoring for security through the detection of structures beneath the ground, to environmental applications such as monitoring chemical agents in the atmosphere.

Within the possible applications of Earth observation with IFS, cases of remote sensing studies of underground military targets have been recorded, which are detected through spectroscopic measurements. In this case, it is noted that the methodology of this application varies locally since Vegetation Indices and Crop Height indices must be determined[32].The development of image slicer techniques aims to create more powerful instruments to achieve higher resolution and sensitivity in data collection. This technology is intended to be applied to Earth observation using sensors to monitor various chemical agents such as CO2, utilizing short-wave infrared.[15]

The use of remote sensing also has important applications in soil chemical determination. For example in [1] a practical case is presented where field spectroscopy integrated with GIS determines crucial parameters of soil erosion in the Mediterranean. An example of a direct application of IFUs is DESIS, launched in 2018 as part of the MUSE instrument, located on the International Space Station (ISS) and taking approximately 5-6 days to orbit Earth. DESIS is a hyperspectral instrument with a maximum resolution of 30m and a spectral range between 400nm and 1000nm. The instrument is equipped with a steering mirror for Bidirectional Reflectance and Distribution Function (BRDF) measurements[21].

One of the possible uses of employing IFS for the creation of spectroscopy images is to use libraries to match absorption signatures in biomaterials[1][49].Planetary surfaces are complex, with Earth's surface being the most varied in our solar system due to its diverse geology, oceans, ice caps, abundant life, and human influences[38]. Other planets feature different geologies and surface compositions. To understand Earth and other planets, scientists create maps of materials and other measurable quantities. Earth surface maps cover themes such as geology, ecosystems, environmental issues, hazards, land management, and global change[24] [18]. Geologic maps reveal formations, soils, mineral occurrences, faults, and building materials. Ecosystem maps detail habitats, vegetation, and riparian zones. Environmental maps address issues like acid rock drainage, oil spills, forest fire potential, and water quality. Hazard maps show

In the context of greenhouse gases,the remote sensing typically involves the use of satellite or aerial sensors to detect and measure gas concentrations in the atmosphere[9].A possible application of IFS is the chemical characterization of greenhouse gases in coral reef marine ecosystems. The following work presents an analysis of how hyperspectral imaging is used to determine the effect of greenhouse gas emissions on this ecosystem[14]n this same field, atmospheric signatures related to greenhouse gas emissions are developed. This is an activity that astronomers have already conducted and can be a direct application of IFS [43][10].

6 Concluding Remarks

In conclusion, Integral Field Spectroscopy continues to play a pivotal role in advancing our understanding of the Universe. With state-of-the-art instruments, advanced data analysis techniques, and innovative scientific applications, IFS remains at the forefront of observational astronomy. As we look towards the future, continued technological developments and interdisciplinary collaborations will further expand the capabilities of IFS and unlock new discoveries about the cosmos.

Integral Field Spectroscopy holds great promise as a technique for remote sensing applications, offering unparalleled capabilities for capturing spatially and spectrally rich datasets. With continued advancements in instrumentation and data analysis techniques, IFS is called to become an indispensable tool for monitoring and understanding Earth's environment. Now a challenge brought by the new applications of IFS for remote sensing lies in data interpretation and the statistical interpretation of this data. Therefore, emphasis must be placed on the development of computational tools for processing these in the context of Earth observation.

References

[1] Dimitrios D. Alexakis et al. "Integrated Use of Satellite Remote Sensing, Artificial Neural Networks, Field Spectroscopy, and GIS in Estimating Crucial Soil Parameters in Terms of Soil Erosion". In: *Remote Sensing* 11.9 (2019). ISSN: 2072-4292. DOI: 10.3390/rs11091106. URL: https://www.mdpi.com/2072-4292/11/9/1106.

[2] Jeremy Allington-Smith. "Basic principles of integral field spectroscopy". In: *New Astronomy Reviews* 50.4 (2006). Integral Field Spectroscopy: Techniques and Data Production, pp. 244–251. ISSN: 1387-6473. DOI: https://doi.org/10.1016/j.newar.2006.02.024. URL: https://www.sciencedirect.com/science/article/pii/S1387647306000157.

[3] Jeremy Allington-Smith. "Basic principles of integral field spectroscopy". In: *New Astronomy Reviews* 50 (June 2006), pp. 244–251. DOI: 10.1016/j.newar.2006.02.024.

[4] J. R. Allington-Smith. "Integral Field Spectroscopy for panoramic telescopes". In: *Revista Mexicana de Astronomía y Astrofísica* 28.1 (June 2007), pp. 17–23. URL: http://www.redalyc.org/pdf/571/57102804.pdf.

[5] Emilien Alvarez-Vanhard, Thomas Corpetti, and Thomas Houet. "UAV satellite synergies for optical remote sensing applications: A literature review". In: *Science of Remote Sensing* 3 (2021), p. 100019. ISSN: 2666-0172. DOI: https://doi.org/10.1016/j.srs.2021.100019. URL: https://www.sciencedirect.com/science/article/pii/S2666017221000067.

[6] Itiya Aneece et al. "New Generation Hyperspectral Data From DESIS Compared to High Spatial Resolution PlanetScope Data for Crop Type Classification". In: *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 15 (Jan. 2022), pp. 7846–7858. DOI: 10.1109/jstars.2022.3204223. URL: https://doi.org/10.1109/jstars.2022.3204223.

[7] J Barrera-Ballesteros et al. "The EDGE-CALIFA survey: self-regulation of star formation at kpc scales". In: *Monthly Notices of the Royal Astronomical Society* 503.3 (Mar. 2021), pp. 3643–3659. DOI: 10.1093/mnras/stab755. URL: https://doi.org/10.1093/mnras/stab755.

[8] Phillip C. Chamberlin and Qian Gong. "An integral field spectrograph utilizing mirrorlet arrays". In: *Journal of geophysical research. Space physics* 121.9 (Sept. 2016), pp. 8250–8259. DOI: 10.1002/2016ja022487. URL: https://doi.org/10.1002/2016ja022487.

[9] Phillip C. Chamberlin et al. "Status Update on the Solar eruptioN Integral Field Spectrograph (SNIFS) Sounding Rocket". In: *AGU Fall Meeting Abstracts*. Vol. 2023. Dec. 2023, SA13C-2493, SA13C–2493.

[10] Ross Cheriton et al. "Fiber Fabry-Perot astrophotonic correlation spectroscopy for remote gas identification and radial velocity measurements". In: 60.32 (Nov. 2021), p. 10252. DOI: 10.1364/AO.430540. arXiv: 2107.04494 [astro-ph.IM].

[11] Haeun Chung et al. "DOTIFS: spectrograph optical and opto-mechanical design". In: *Ground-based and Airborne Instrumentation for Astronomy VII*. Ed. by Christopher J. Evans, Luc Simard, and Hideki Takami. Vol. 10702. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. July 2018, 107027A, 107027A. DOI: 10.1117/12.2311594. arXiv: 1810.03621 [astro-ph.IM].

[12] Roger N. Clark et al. "Imaging spectroscopy: Earth and planetary remote sensing with the USGS Tetracorder and expert systems". In: *Journal of Geophysical Research: Planets* 108.E12 (2003). DOI: https://doi.org/10.1029/2002JE001847. eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2002JE001847. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002JE001847.

[13] Delgado-Correal. *On the Optical Properties of Cosmic Telescopes: A Spectroscopy study of the inner core of a Massive Galaxy Cluster*. June 2018. URL: https://iris.unife.it/handle/11392/2488322.

[14] Shubhankar Deshpande et al. "Learning Radiative Transfer Models for Climate Change Applications in Imaging Spectroscopy". In: *arXiv e-prints*, arXiv:1906.03479 (June 2019), arXiv:1906.03479. DOI: 10.48550/arXiv.1906.03479. arXiv: 1906.03479 [cs.LG].

[15] *Development of Integral Field Unit (IFU) Spectrometers*. URL: https://ceoi.ac.uk/technologies/optical-spectroscopy/development-of-ifu-spectrometers/.

[16] G. Filacchione et al. "The Integral-Field Imager and Spectrometer for planetary exploration (fISPEx)". In: *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V*. Ed. by Ramón Navarro and Roland Geyl. Vol. 12188. International Society for Optics and Photonics. SPIE, 2022, p. 1218809. DOI: 10.1117/12.2626982. URL: https://doi.org/10.1117/12.2626982.

[17] Luis Guanter et al. "The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation". In: *Remote Sensing* 7.7 (2015), pp. 8830–8857. ISSN: 2072-4292. DOI: 10.3390/rs70708830. URL: https://www.mdpi.com/2072-4292/7/7/8830.

[18] K. E. Harborne et al. "SimSpin v2.6.0—constructing synthetic spectral IFU cubes for comparison with observational surveys". In: *Publications of the Astronomical Society of Australia* 40 (Jan. 2023). DOI: 10.1017/pasa.2023.47. URL: https://doi.org/10.1017/pasa.2023.47.

[19] Vicki L. Herde et al. "The Solar EruptioN Integral Field Spectrograph". In: 299.8, 120 (Aug. 2024), p. 120. DOI: 10.1007/s11207-024-02367-y. arXiv: 2407.08834 [astro-ph.SR].

[20] information@eso.org. *Integral field units*. URL: https://www.eso.org/public/teles-instr/technology/ifu/.

[21] *ISS: MUSES (Multi-User System for Earth Sensing) - eoPortal*. July 2022. URL: https://www.eoportal.org/satellite-missions/iss-muses#MusesDesis.html.10.

[22] Jiale Jiang et al. "Multi-sensor and multi-platform consistency and interoperability between UAV, Planet CubeSat, Sentinel-2, and Landsat reflectance data". In: *GIScience Remote Sensing* 59.1 (June 2022), pp. 936–958. DOI: 10.1080/15481603.2022.2083791. URL: https://doi.org/10.1080/15481603.2022.2083791.

[23] Shoko Jin et al. "The wide-field, multiplexed, spectroscopic facility WEAVE: Survey design, overview, and simulated implementation". In: *Monthly Notices of the Royal Astronomical Society* 530.3 (Mar. 2023), pp. 2688–2730. DOI: 10.1093/mnras/stad557. URL: https://doi.org/10.1093/mnras/stad557.

[24] Mathieu G. A. Lapôtre et al. "Probing space to understand Earth". In: *Nature Reviews Earth Environment* 1.3 (Mar. 2020), pp. 170–181. DOI: 10.1038/s43017-020-0029-y. URL: https://doi.org/10.1038/s43017-020-0029-y.

[25] Florence Laurent and François Hénault. "Collimating slicer for optical integral field spectroscopy". In: *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE* (July 2016). DOI: 10.1117/12.2231701. URL: https://doi.org/10.1117/12.2231701.

[26] Haosheng Lin et al. "Development of Integral Field Spectrographs to Revolutionize Spectroscopic Observations of Solar Flares and other Energetic Solar Eruptions". In: *Bulletin of the American Astronomical Society*. Vol. 55. July 2023, 239, p. 239. DOI: 10.3847/25c2cfeb.20fe40d5. arXiv: 2209.00788 [astro-ph.IM].

[27] Dou Liu, Michael R. Blanton, and David R. Law. "Covariance-regularized Reconstruction of Data Cubes in Integral Field Spectroscopy and Application to MaNGA Data". In: 159.1, 22 (Jan. 2020), p. 22. DOI: 10.3847/1538-3881/ab5aeb. arXiv: 1906.06369 [astro-ph.GA].

[28] Alexander Madurowicz and Bruce Macintosh. "Integral Field Spectroscopy with the Solar Gravitational Lens". In: *Astrophysical journal/The Astrophysical journal* 930.1 (May 2022), p. 19. DOI: 10.3847/1538-4357/ac5e9d. URL: https://doi.org/10.3847/1538-4357/ac5e9d.

[29] Vincenzo Mainieri et al. *The Wide-Field Spectroscopic Telescope (WST) Science White Paper*. Mar. 2024. URL: https://arxiv.org/abs/2403.05398.

[30] E. Mármol-Queraltó et al. "Integral field spectroscopy of a sample of nearby galaxies". In: *Astronomy astrophysics* 534 (Sept. 2011), A8. DOI: 10.1051/0004-6361/201117032. URL: https://doi.org/10.1051/0004-6361/201117032.

[31] Alessandro Mei et al. "Integration of Field and Laboratory Spectral Data with Multi-Resolution Remote Sensed Imagery for Asphalt Surface Differentiation". In: *Remote sensing* 6.4 (Mar. 2014), pp. 2765–2781. DOI: 10.3390/rs6042765. URL: https://doi.org/10.3390/rs6042765.

[32] George Melillos et al. "Integrated use of field spectroscopy and satellite remote sensing for defence and security applications in Cyprus". In: May 2016, p. 982316. DOI: 10.1117/12.2223438.

[33] B. W. Miller. "3D Spectroscopy and the Virtual Observatory". In: *Astronomical Spectroscopy and Virtual Observatory*. Ed. by M. Guainazzi and P. Osuna. Oct. 2008, p. 117. DOI: 10.48550/arXiv.0708.2111. arXiv: 0708.2111 [astro-ph].

[34] Bryan W. Miller. *3D Spectroscopy and the Virtual Observatory*. Aug. 2007. URL: https://arxiv.org/abs/0708.2111.

[35] E. J. Milton. "Review Article Principles of field spectroscopy". In: *International Journal of Remote Sensing* 8.12 (Dec. 1987), pp. 1807–1827. DOI: 10.1080/01431168708954818. URL: https://doi.org/10.1080/01431168708954818.

[36] Edward J. Milton et al. "Progress in field spectroscopy". In: *Remote sensing of environment* 113 (Sept. 2009), S92–S109. DOI: 10.1016/j.rse.2007.08.001. URL: https://doi.org/10.1016/j.rse.2007.08.001.

[37] Thomas Peschel et al. "Integration and testing of an imaging spectrometer for earth observation". In: *International Conference on Space Optics — ICSO 2018* (July 2019). DOI: 10.1117/12.2535943. URL: https://doi.org/10.1117/12.2535943.

[38] David C. Pieri and Adam M. Dziewonski. "Chapter 21 - Earth as a Planet: Surface and Interior". In: *Encyclopedia of the Solar System (Third Edition)*. Ed. by Tilman Spohn, Doris Breuer, and Torrence V. Johnson. Third Edition. Boston: Elsevier, 2014, pp. 445–478. ISBN: 978-0-12-415845-0. DOI: https://doi.org/10.1016/B978-0-12-415845-0.00021-9. URL: https://www.sciencedirect.com/science/article/pii/B9780124158450000219.

[39] Deqing Ren and Jeremy Allington-Smith. "On the Application of Integral Field Unit Design Theory for Imaging Spectroscopy". In: 114.798 (Aug. 2002), pp. 866–878. DOI: 10.1086/341710.

[40] M. Rodenhuis et al. "Five-dimensional optical instrumentation: combining polarimetry with time-resolved integral-field spectroscopy". In: *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE* (June 2014). DOI: 10.1117/12.2053241. URL: https://doi.org/10.1117/12.2053241.

[41] Martin M. Roth and Christer Sandin. "Visualization of Data from Integral Field Spectroscopy and the P3d Tool". In: *arXiv e-prints*, arXiv:1011.6189 (Nov. 2010), arXiv:1011.6189. DOI: 10.48550/arXiv.1011.6189. arXiv: 1011.6189 [astro-ph.IM].

[42] K. B. Schmidt et al. "Three-Dimensional Optimal Spectral Extraction (TDOSE) from integral field spectroscopy". In: *Astronomy and Astrophysics* 628 (Aug. 2019), A91. DOI: 10.1051/0004-6361/201935857. URL: https://doi.org/10.1051/0004-6361/201935857.

[43] Edward W. Schwieterman et al. "Artificial Greenhouse Gases as Exoplanet Technosignatures". In: 969.1, 20 (July 2024), p. 20. DOI: 10.3847/1538-4357/ad4ce8. arXiv: 2405.11149 [astro-ph.EP].

[44] Freek D. van der Meer et al. "Multi- and hyperspectral geologic remote sensing: A review". In: *International Journal of Applied Earth Observation and Geoinformation* 14.1 (2012), pp. 112–128. ISSN: 1569-8432. DOI: https://doi.org/10.1016/j.jag.2011.08.002. URL: https://www.sciencedirect.com/science/article/pii/S0303243411001103.

[45] Sébastien Vivès and Eric Prieto. "An original image slicer designed for Integral Field Spectroscopy with NIRSpec/JSWT". In: *arXiv e-prints*, physics/0512002 (Dec. 2005), physics/0512002. DOI: 10.48550/arXiv.physics/0512002. arXiv: physics/0512002 [physics.optics].

[46] John R. Walsh and M. M. Roth. "Developing 3D spectroscopy in Europe". In: *Msngr* 109 (Sept. 2002), pp. 54–56. URL: http://www.eso.org/sci/publications/messenger/archive/no.109-sep02/messenger-no109-54-56.pdf.

¡Gracias por su atención!